UCRL-MI-231093

IFE Science and Technology Strategic Planning Workshop - Part 3: April 26, 2007 Presentations

To select an individual presentation, click the table of contents entry on the next page or click the title on the agenda for Day 3 (using the Hand Tool icon).

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Part 3 Contents

Technical Program

Day 1, Tuesday, April 24

Overviews - Approaches to IFE

7:00-8:00 Registration and Continental Breakfast

All Day Plenary Session

8:00-8:30 Workshop Motivation and Objectives (Ed Synakowski, LLNL)
8:30-9:00 Setting the Stage for IFE and Workshop Overview (Wayne Meier, LLNL)

Following speakers to address current status, near-term plans, long-range visions and funding needs to move to the next step for the particular approach. With respect to planning, address

- How do you see your approach evolving beyond the near term?
- What needs to be accomplished to move forward on such a strategy?
- What are the potential landscape-changing developments?
- What are the technical issues for your approach?

9:00-9:30 HAPL/KrF (John Sethian, NRL)
9:30-9:40 Q&A

9:40-10:00 Break

10:00-10:30 DPSSL (Al Erlandson, LLNL)
10:30-11:00 Discussion

11:00-11:30 FTF (Steve Obenschain, NRL)
11:30-12:00 Discussion

12:00-1:00 Lunch

1:00-1:30 HIF (Grant Logan, LBNL)
1:30-2:00 Discussion

2:00-2:30 Z-IFE (Craig Olson, SNL)
2:30-3:00 Discussion

3:00-3:15 Break

3:15-3:45 FI as a Cross-Cutting Option for IFE (Mike Campbell, GA)
3:45-4:00 Discussion

4:00-4:30 The Potential Benefits of Magnetic Fields in Inertially Confined Plasmas (Bruno Bauer, UNR)
4:30-4:45 Discussion

4:45-6:00 Panel Discussion (M. Campbell, S. Dean, G. Logan, C. Olson, C. Sangster, J. Sethian, E. Synakowski)
What can/should we do to be prepared to take advantage of growing interest in and funding for IFE that could be triggered by a variety of events (e.g., successful ignition on NIF, increase concern about global climate change, increase interest in domestic energy sources, etc.)?

Day 2, Wednesday, April 25

Working Together in the Near-Term to Advance IFE and Related Science

7:30-8:00 Continental Breakfast

Interagency Approach to High Energy Density Laboratory Plasmas (HEDLP)
8:00-8:20 Overview of the National Task Force Report on HEDP: Setting the Stage (Ron Davidson, PPPL)
8:20-8:50 OFES, NNSA Perspectives (Ray Fonck, OFES; and Chris Keane, NNSA)
8:50-9:15 Updated Planning for HED-LP (Francis Thio, OFES)
9:15-9:45 Discussions

9:45-10:00 Break

Plenary Talks: Existing and near-term ICF/HEDP capabilities and research plans focusing on R&D relevant to IFE
Questions to focus the plenary talks include:
- What are the HEDP questions that can be addressed in the near-term that are relevant to IFE? How can NNSA facilities be used to support IFE both now and post ignition?
- What are current or planned interactions with the other communities (ICF/HEDP/IFE)?
- Who are the customers for this HEDP science besides the IFE/ICF community?

ICF/HEDP Facilities and R&D:
10:00-10:45 NIC and NIF (John Lindl, LLNL)
10:45-11:15 Omega (John Soures, UR-LLE)
11:15-11:45 Z-pinch (Keith Matzen, SNL)
11:45-12:15 Nike--1) ICF Experiments and Plans, 2) ICF Physics Issues (Andy Schmitt, NRL)

12:15-1:15 Lunch

1:15-1:45 Advanced Ignition (Fast and other two-step ignition) (Riccardo Betti, UR-LLE)
1:45-2:15 HIFS/WDM/Hydrodynamics Experiments on NDCX-I and NDCX-II (John Barnard, LLNL)
2:15-2:45 A Pathway to HEDP: Magnetized Target Fusion (Glen Wurden, LANL)

2:45-3:00 Break

3:00-5:00 PM - Breakout Session - Working Together to Advance IFE and Related Science*
Four groups. Same questions for each group:
- What are the HEDP questions that can be addressed in IFE-relevant NNSA and OFES facilities? Which questions are directly relevant to IFE? What types of IFE relevant experiments can be done on NNSA ICF facilities?
- How does addressing these questions enable progress in IFE?
- What opportunities exist that can be captured with growing budgets?
- How are the IFE/ICF/HEDP communities working together to maximize use of limited resources to advance the underlying science of IFE? What obstacles exist? How can these working relationships be improved?

***Breakout group leaders to prepare a single summary talk to be given the final day.**

Day 3, Thursday, April 26

International Perspective and IFE Science and Technology in the Long Term

7:30-8:00 Continental Breakfast

International Activities
8:00-8:30 FIREX Project (Hiroshi Azechi, ILE, Osaka, Japan)
8:30-9:00 HiPER and other EU Activities (Mike Dunne, UK)
9:00-9:30 IAEA Coordinated Research Program on IFE (Neil Alexander, GA)

9:30-10:00 Discussion on opportunities for international collaborations

10:00-10:15 Break

10:15 AM-12:00 PM – Contributed/Solicited talks (~ 5 @ 15-20 min each)
Other (non-driver) Enabling and Cross-Cutting Science and Technology
- A Survey of Advanced Target Options for IFE (John Perkins, LLNL)
- Ion-Driven Fast Ignition: Scientific Challenges and Tradeoffs (Juan Fernandez, LANL)
- Thick Liquid Protection for Inertial Fusion Energy Chambers (Per Peterson, UCB)
- Dry Wall Chamber Designs (Rene Raffray, UCSD)
- Status of Developing Target Supply Methodologies for Inertial Fusion (Dan Goodin, GA)

12:00-1:00 PM - Lunch

1:00-3:00 Poster Session (contributed posters)

3:00-5:00 PM - Breakout Session - IFE Planning*
Four groups. Same questions for each group:
- What are the elements of a compelling breakout strategy for IFE?
- What advances have to be made to make such a strategy credible?
- What advances can only be made with increased funding?
- Have views of an IFE development path changed since FESAC report? If so, how?

***Breakout group leaders to prepare a single summary talk to be given the final day.**

Day 4, Friday, April 27

Next Generation and Next Steps

8:00-8:30 Continental Breakfast

8:30-10:00 AM - Panel Discussion
Training the Next Generation: University Participation in HEDP and IFE Science and Technology
(5 minute introductions + Discussion)
(Bruno Bauer, UNR; Farhat Beg, UCSD; Linn Van Woerkom, OSU; Shahram Sharafat, UCLA; Brian Wirth, UCB)

10:00-10:15 Break

Summaries from Breakout sessions
(up to 30 minute presentation plus 15 minute discussion)

10:15-11:00 Wednesday Breakout Summary: HEDP Opportunities for IFE (Ed Synakowski, LLNL)
11:00-11:45 Thursday Breakout Summary: IFE Planning (Steve Dean, FPA)

11:45 AM - 12:00 PM - Concluding Remarks, Action Items, Next Steps

12:00 PM - Adjourn

FIREX Project–Its Goal and Current Status

IFE Science and Technology
Strategic Planning Workshop
San Ramon, California
April 24 - 27, 2007

H. Azechi et al.
Vice Director
Institute of Laser Engineering
Osaka University

Outlines

ILE OSAKA

- FIREX Introduction
- FIREX Current Status
- FIREX Role in Japanese Fusion Policy

Since a fuel is heated much faster than pressure equilibrium, a high-density hot-spark is able to be created.

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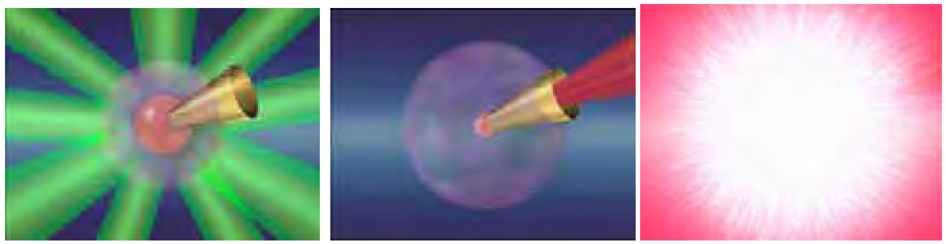
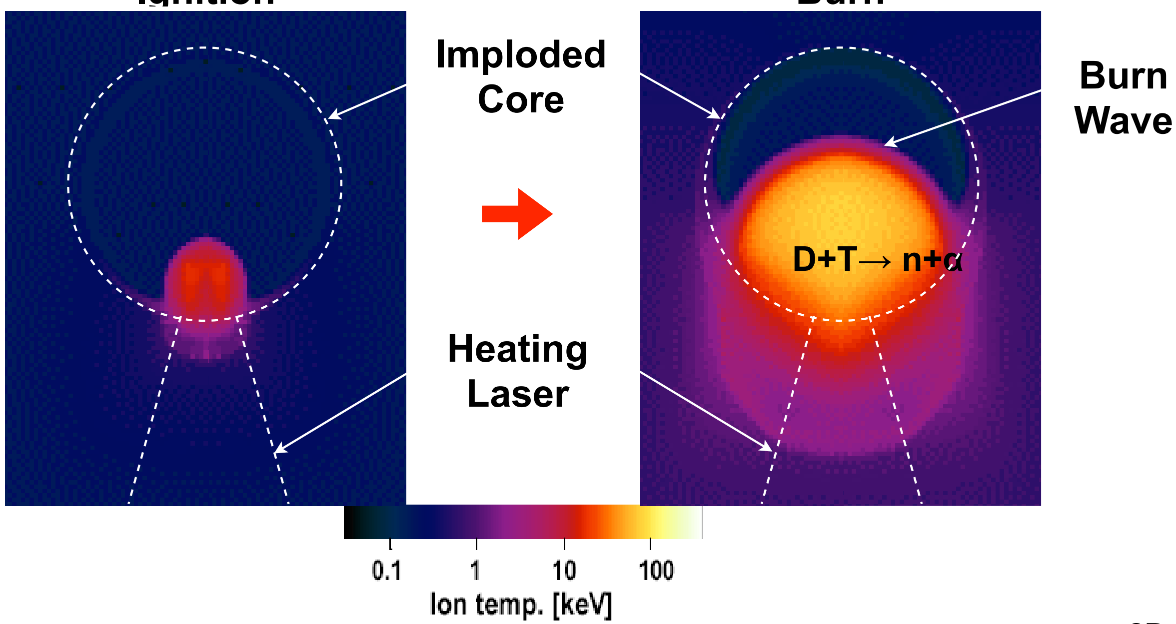
Implosion **Fast Heating** **Ignition/Burn**



Ignition **Burn**



2D simulation by
T. Johzaki, IFSA03

Fast ignition has a potential to be a compact route to IFE.

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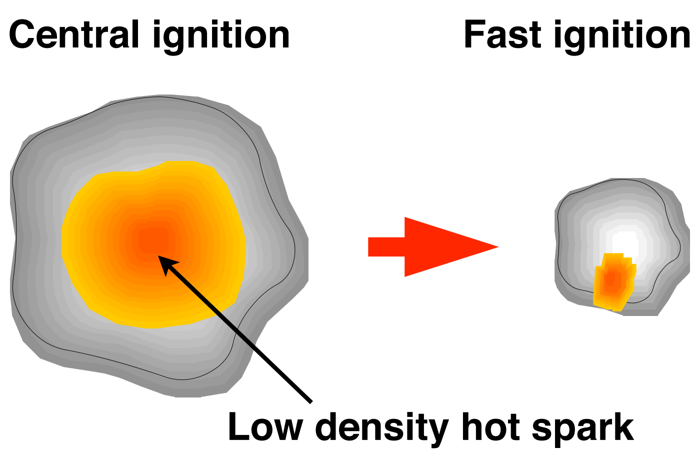
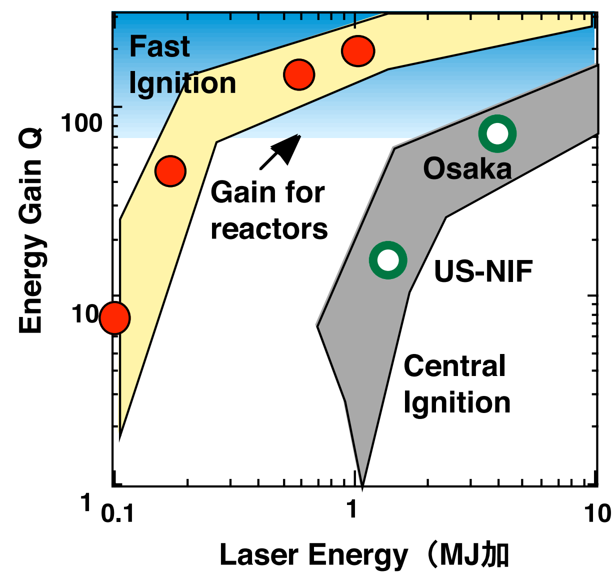
Confinement time = fuel thick / burn wave velocity
Targets with the same thickness results in the same Q





High-density compression and efficient heating are the two major milestones.

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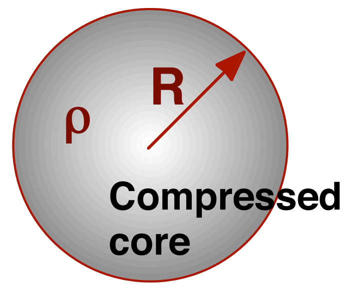
Required energy for igniton is given by

$$\eta E_{laser} = \frac{4\pi}{3} R^3 \rho \cdot \varepsilon_h = \frac{4\pi}{3} \frac{(\rho R)^3}{\rho^2} \varepsilon_h$$

where

$\rho R \approx \alpha$ particle range = 0.3 g/cm ^{2}

ε_h =2(3/2)T/m_{dt}= 1.15 GJ/g @T=10 keV.



To achieve ignition with reasonable size of $E_{laser} \approx$ 10 's kJ, we need

$\rho \approx$ 200 g/cm^3 (1000XLD)
$\eta \approx$ 0.3

The imploded density of cone targets falls in the scaling of of no-cone implosion.

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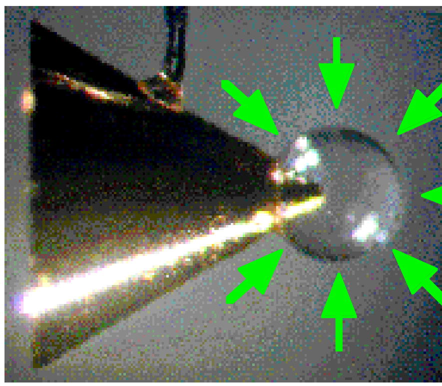
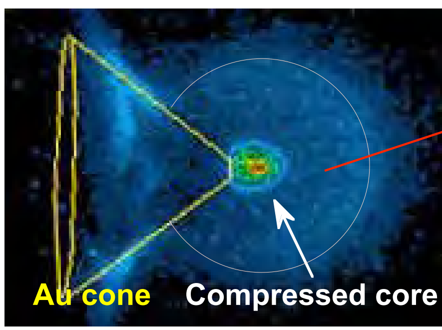
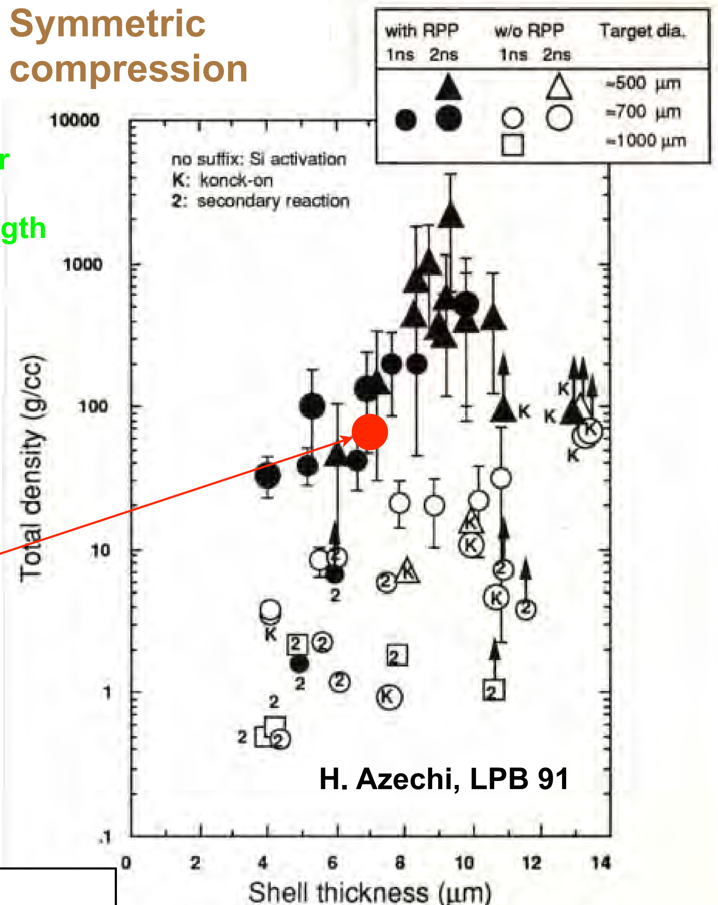
Asymmetric compression



Implosion Laser
GEKKO-XII
0.5-µm wavelength
3 kJ/1.2 ns



Symmetric compression



The implosion velocity is supersonic (M≈20-30), while the rarefaction wave travels along the shell with sonic velocity.

High efficiency (20-30%) heating has been demonstrated. Does the similar efficiency hold in reactor plasmas?

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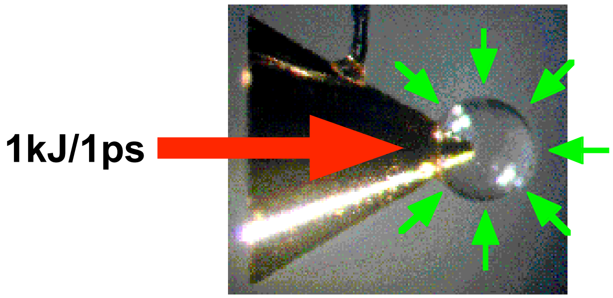
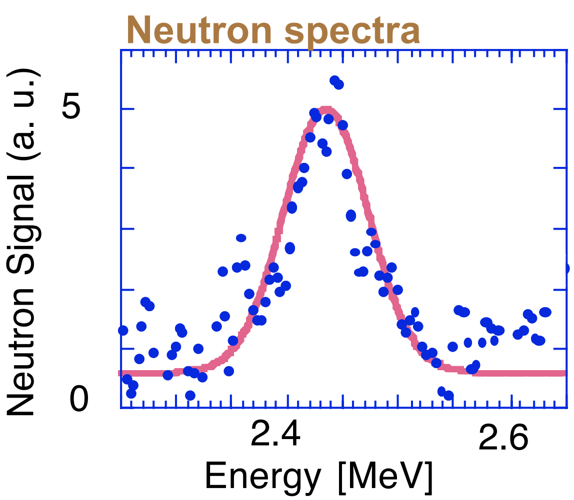
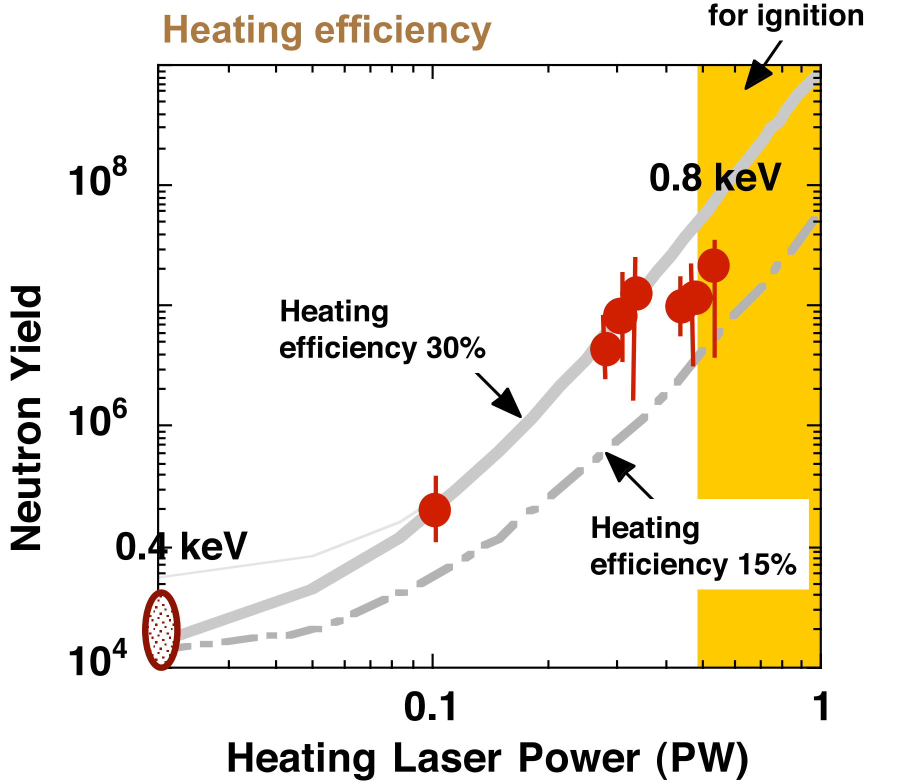
Implosion + Heating







R. Kodama, Nature 01&02

Keeping the laser power minimizes uncertainty of laser-plasma interaction problem.

Fast Ignition Realization EXp't, FIREX

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Implosion Fast Heating Ignition/Burn

- preliminary: Demo of 600 times liquid density
  Demo of 1 keV temp. by 1kJ/1ps.

- FIREX-I：Demo of 5-10 keV temperature by 10kJ/10ps.

- FIREX-II: Demo of ignition and burn by FI

Burning in a reactor plasma

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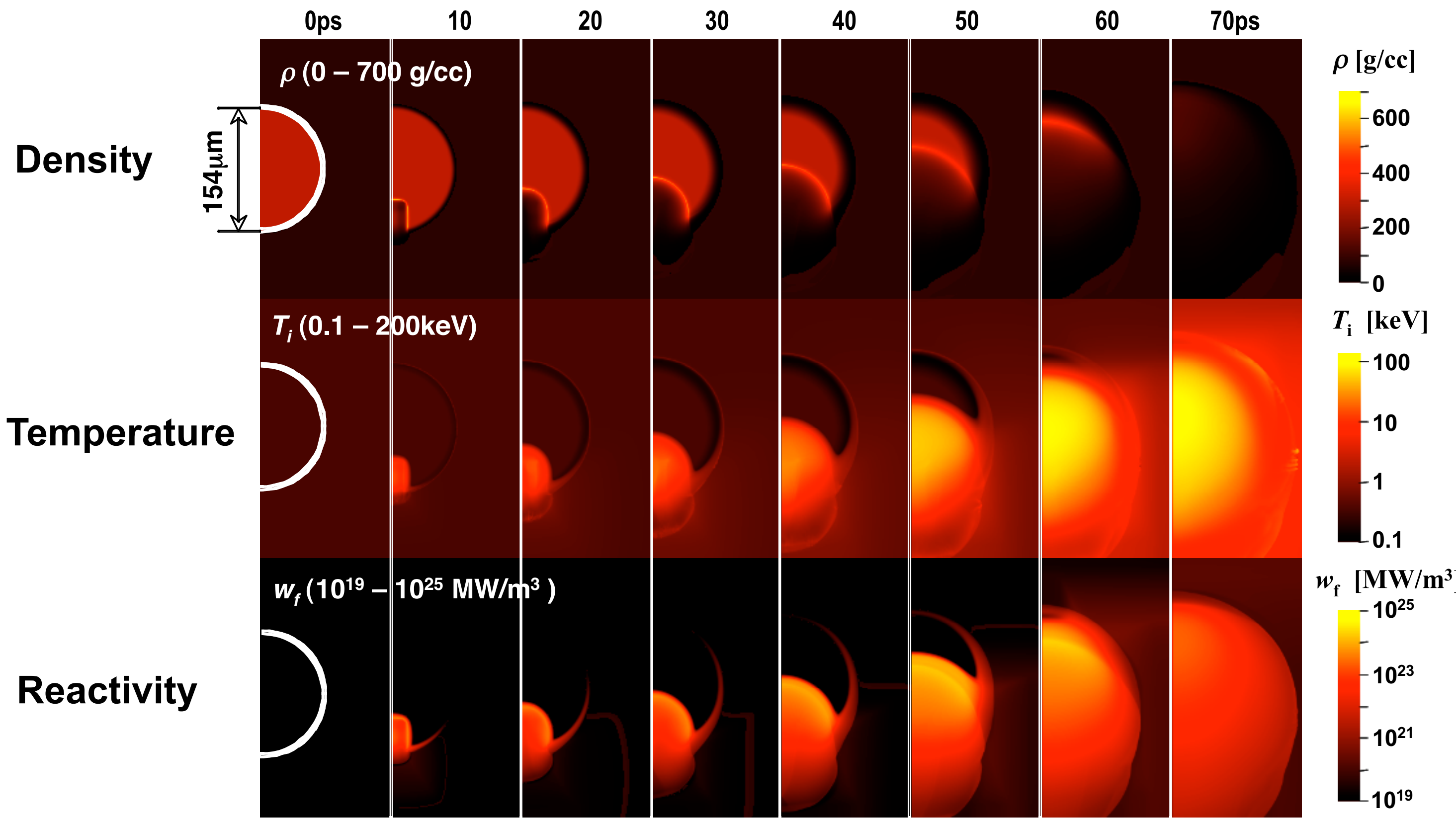

Johzaki 03-07

Detonation velocity >> Hydro velocity

FIREX and Reactor plasma

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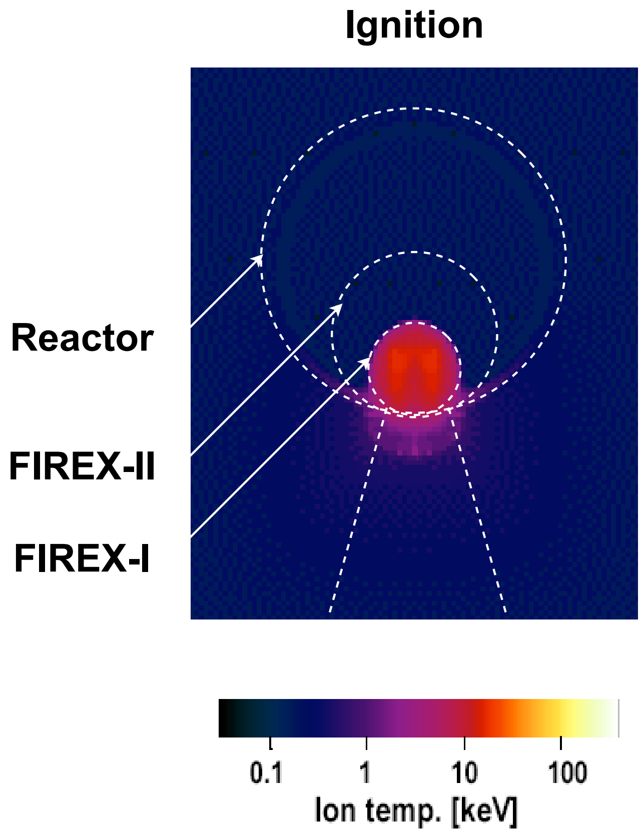

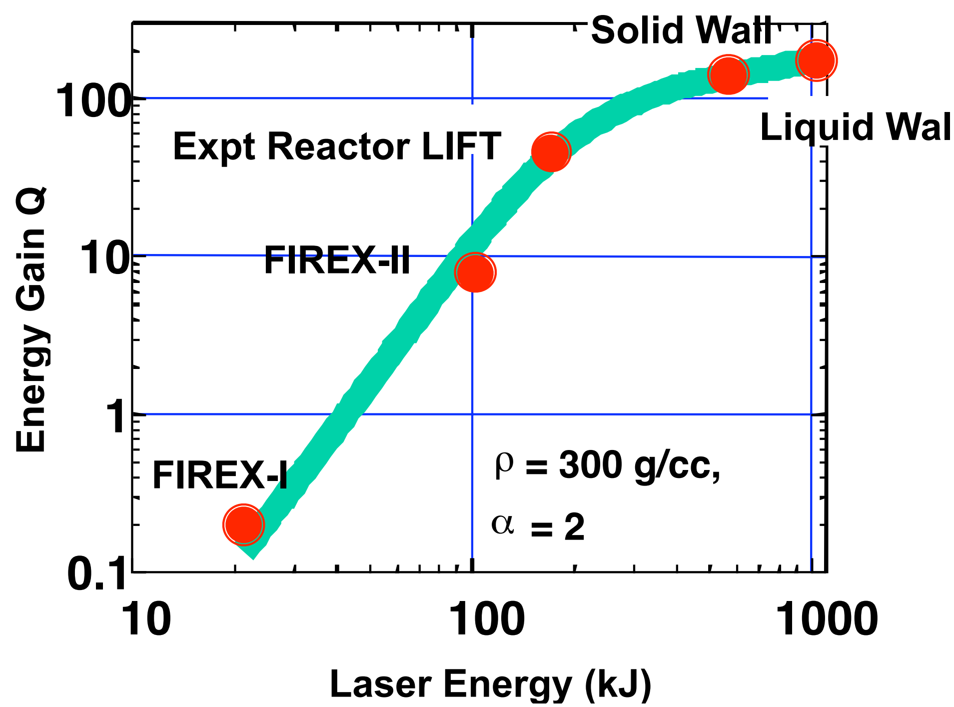

No essential difference in plasma physics from FIREX-II to reactor core plasma.

T. Johzaki, IFSA03

The heating laser delivered designed energy at broadband operation.

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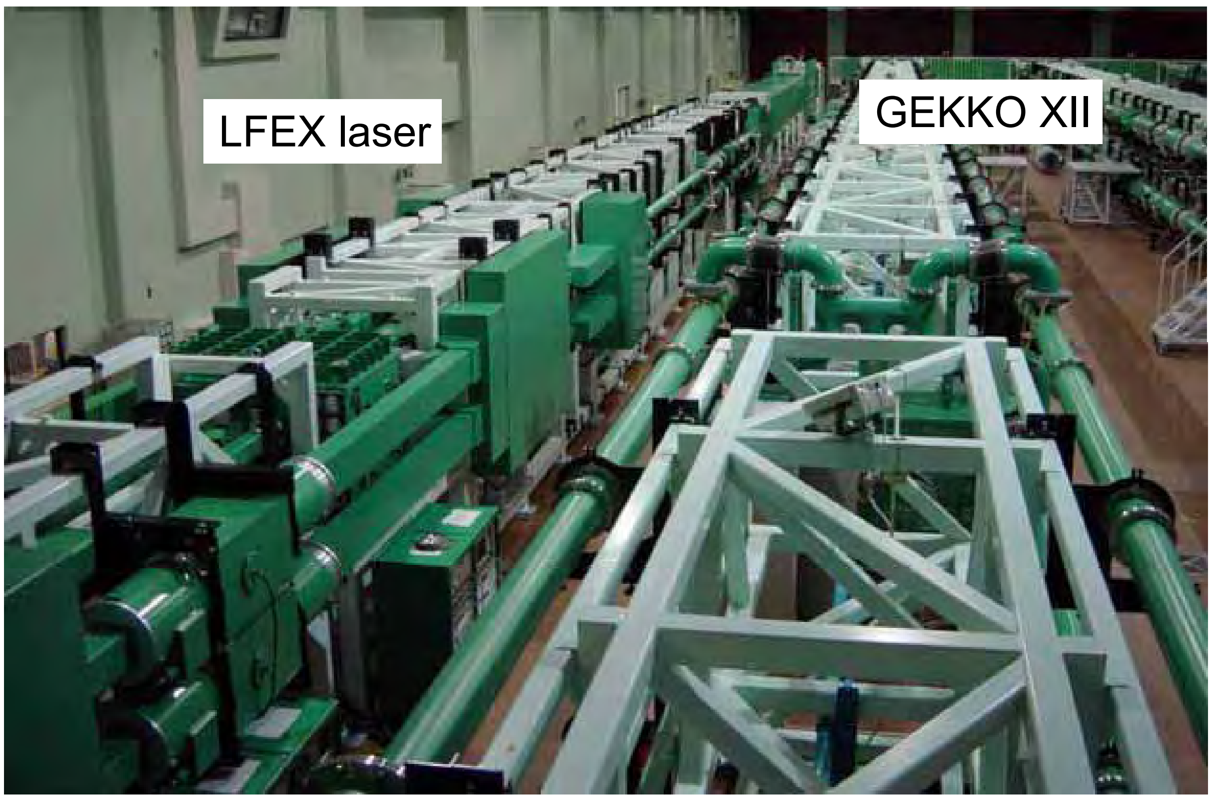
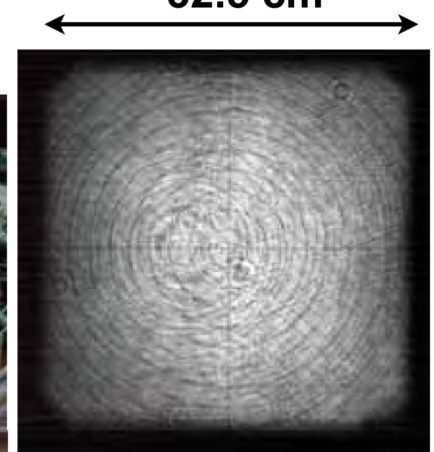
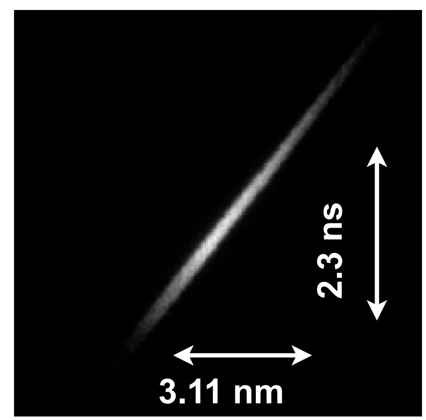
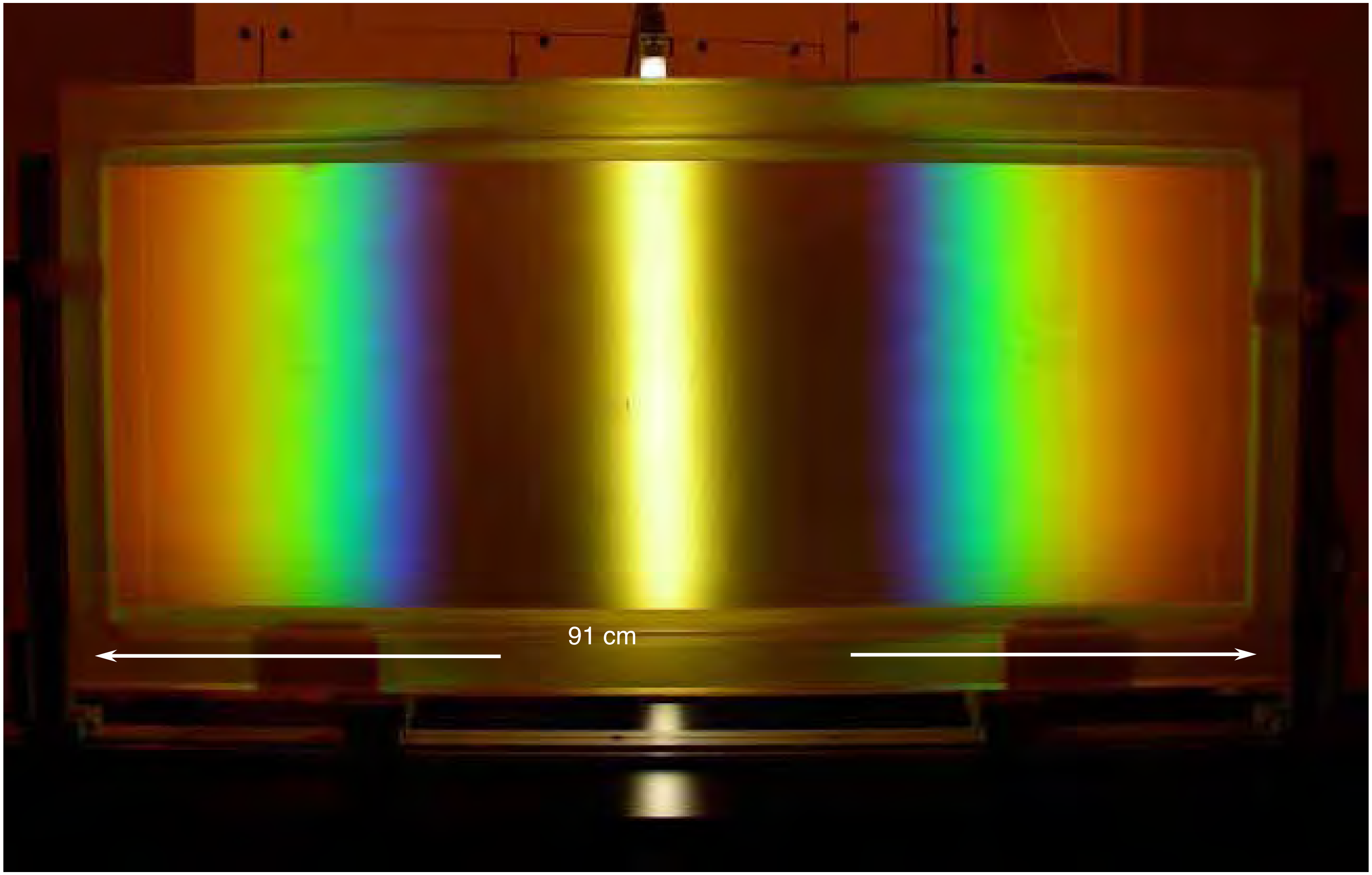
07.2.21 2.9 kJ/beam @broadband (goal=3 kJ/beam)







Large format grating made with phase lock scanning exposure



Proposed FIREX-II **Ignition and Burn**

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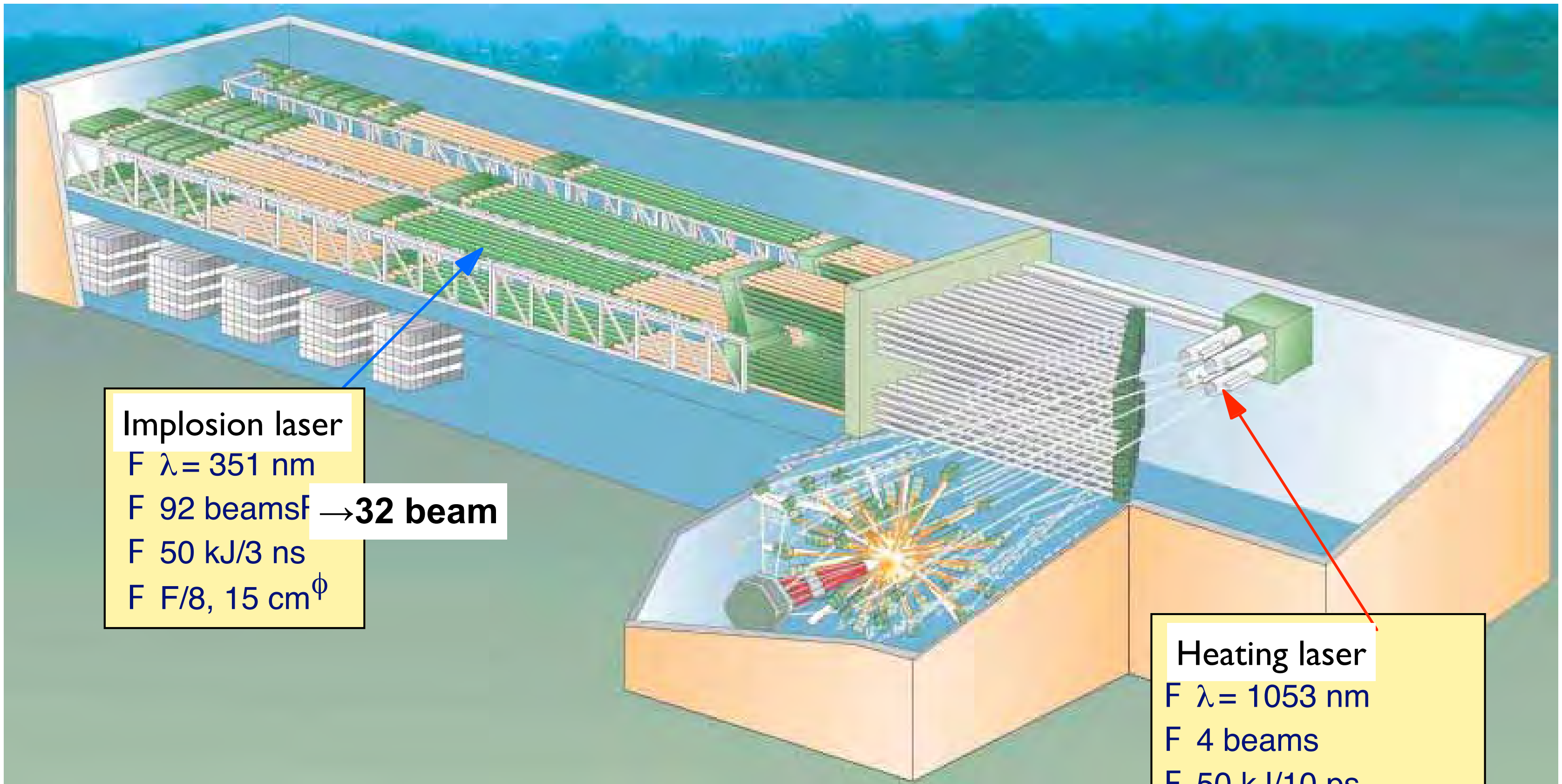
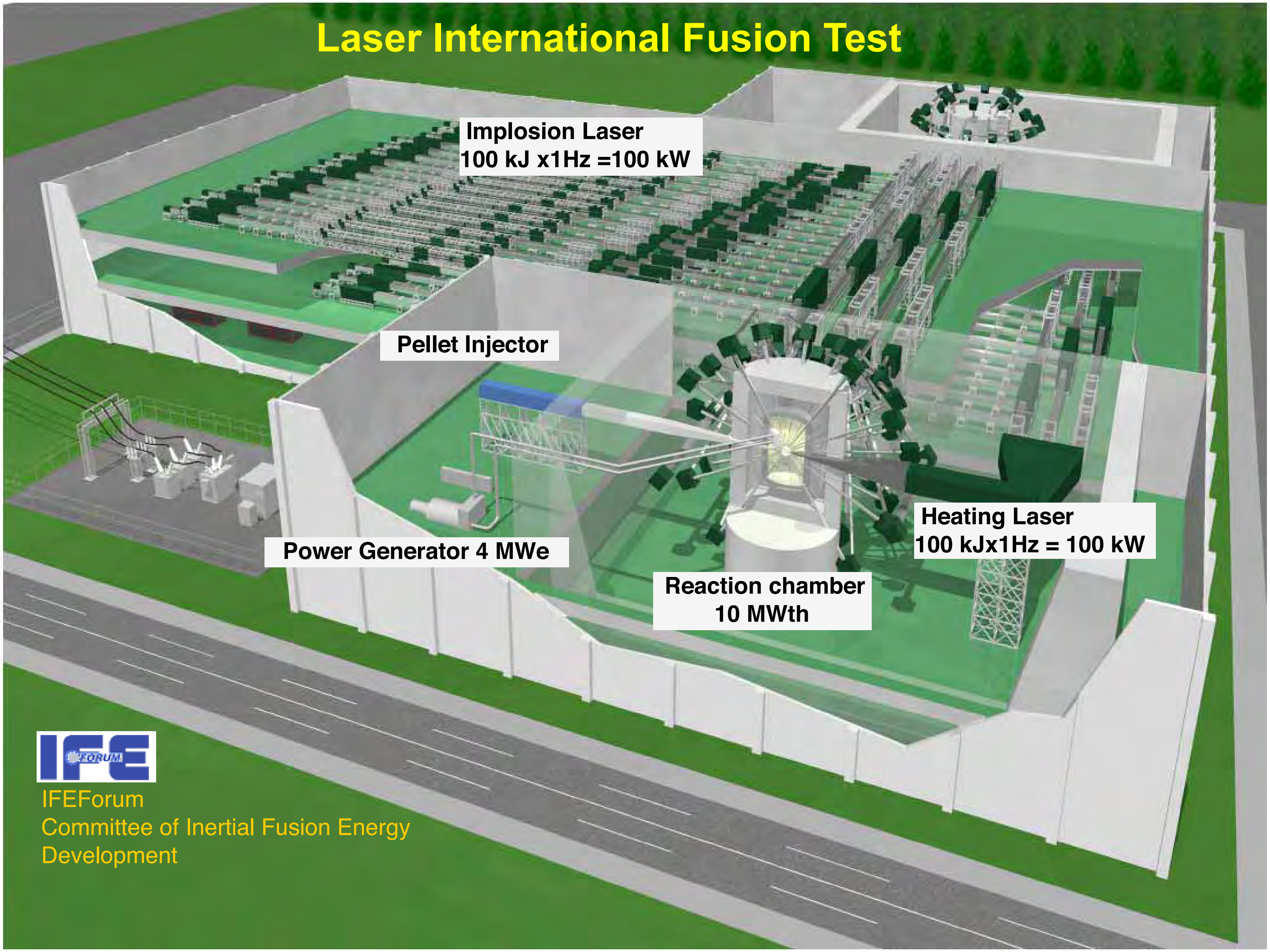


Implosion laser
F λ= 351 nm
F 92 beamsF **→32 beam**
F 50 kJ/3 ns
F F/8, 15 cm$^{\phi}$

Heating laser
F λ= 1053 nm
F 4 beams
F 50 kJ/10 ps
F F/5, 100 cm$^{\phi}$


Laser International Fusion Test
Implosion Laser
100 kJ x1Hz =100 kW
Pellet Injector
Power Generator 4 MWe
Reaction chamber
10 MWth
Heating Laser
100 kJx1Hz = 100 kW
IFE FORUM
IFEForum
Committee of Inertial Fusion Energy
Development

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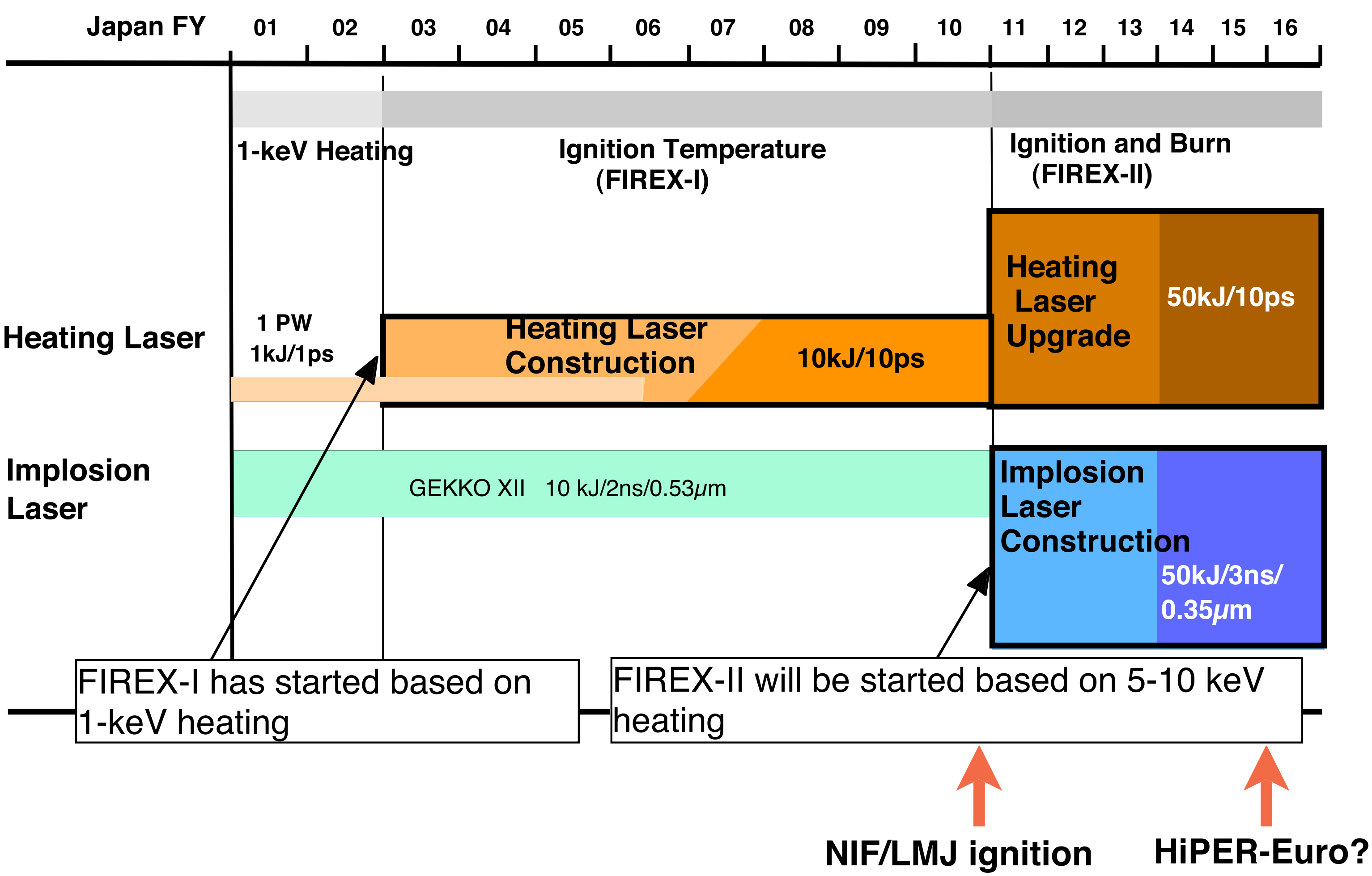
Sub-ignition and ignition by FIREX-I and NIF/LMJ will provide concrete basis of stating FIREX-II and HiPER-Euro.



FIREX-I Time table

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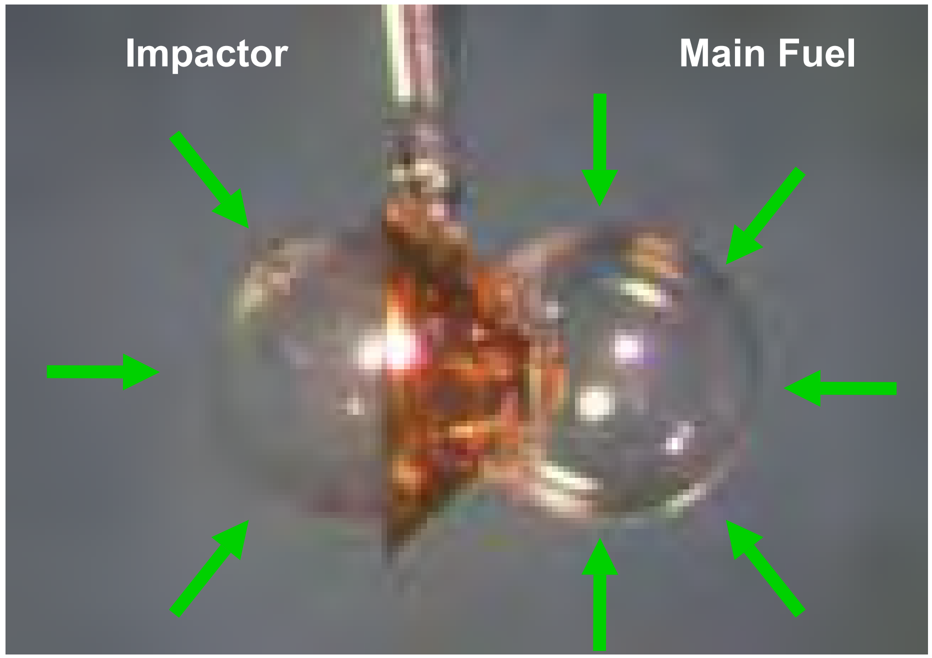
	Construction	Milestones
2005	Laser Construction	
2006	Compressor Architecture	
2007	1-beam operation	CD target heating
2008	4-beam operation	CD target heating
2009	Deformable mirror	D2 heating
2010	Amplitude combination	DT heating (Q=0.1加

Excess achievement will help to approve FIREX-II

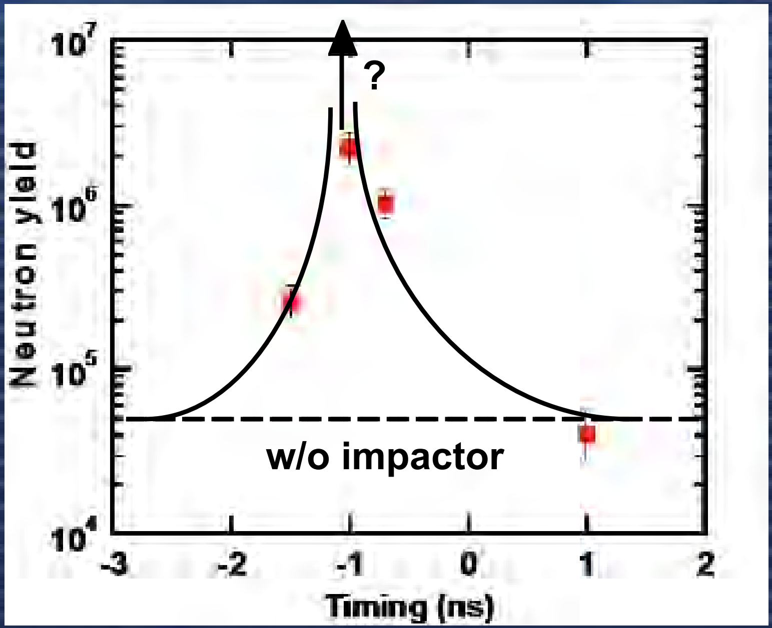
Impact Fast Ignition
–Another Pathway to Ignition–

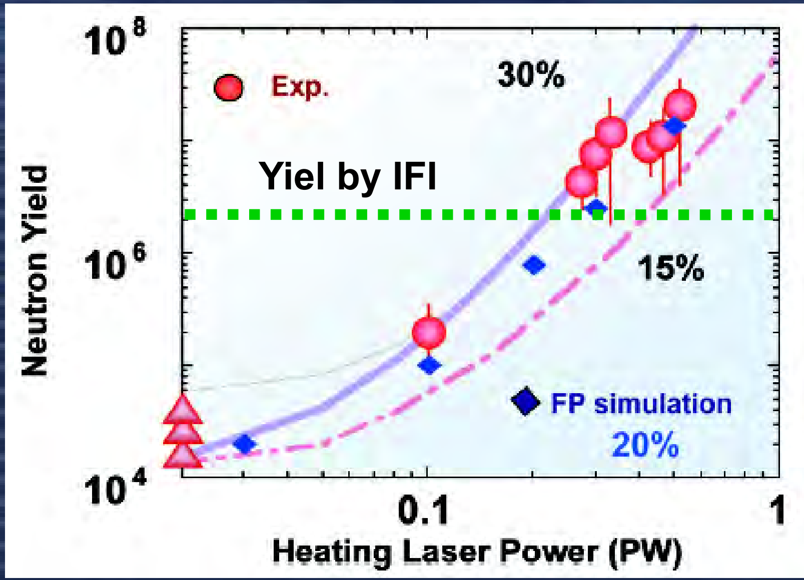


J-US Fast Ignition Workshop 07
9-11 January 2007
Otsu, Jaban

T. Sakaiya, H. Azechi et al.
Institute of Laser Engineering
Osaka University

Neutron yield is enhanced by a factor of 100.





Dèng Xiǎopíng says

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It doesn't matter if an energy carrier is particles or hydro, so long as it generates more neutrons.

Status of Laser Fusion in Japanese Fusion Policy

Under the ITER construction.....

Science Council for Science and Technology has established the Grand Design of Japanese Fusion Research on January 2003.

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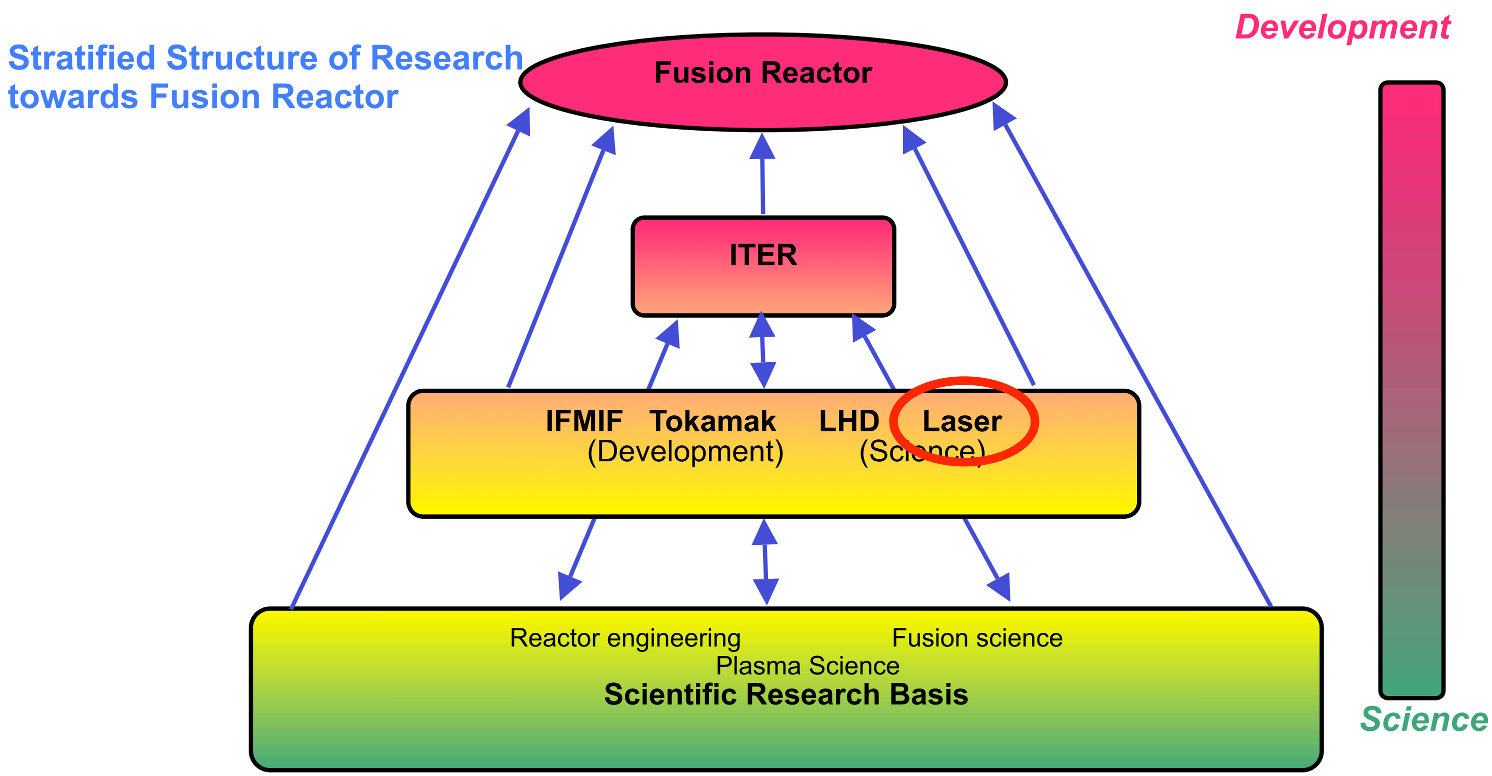
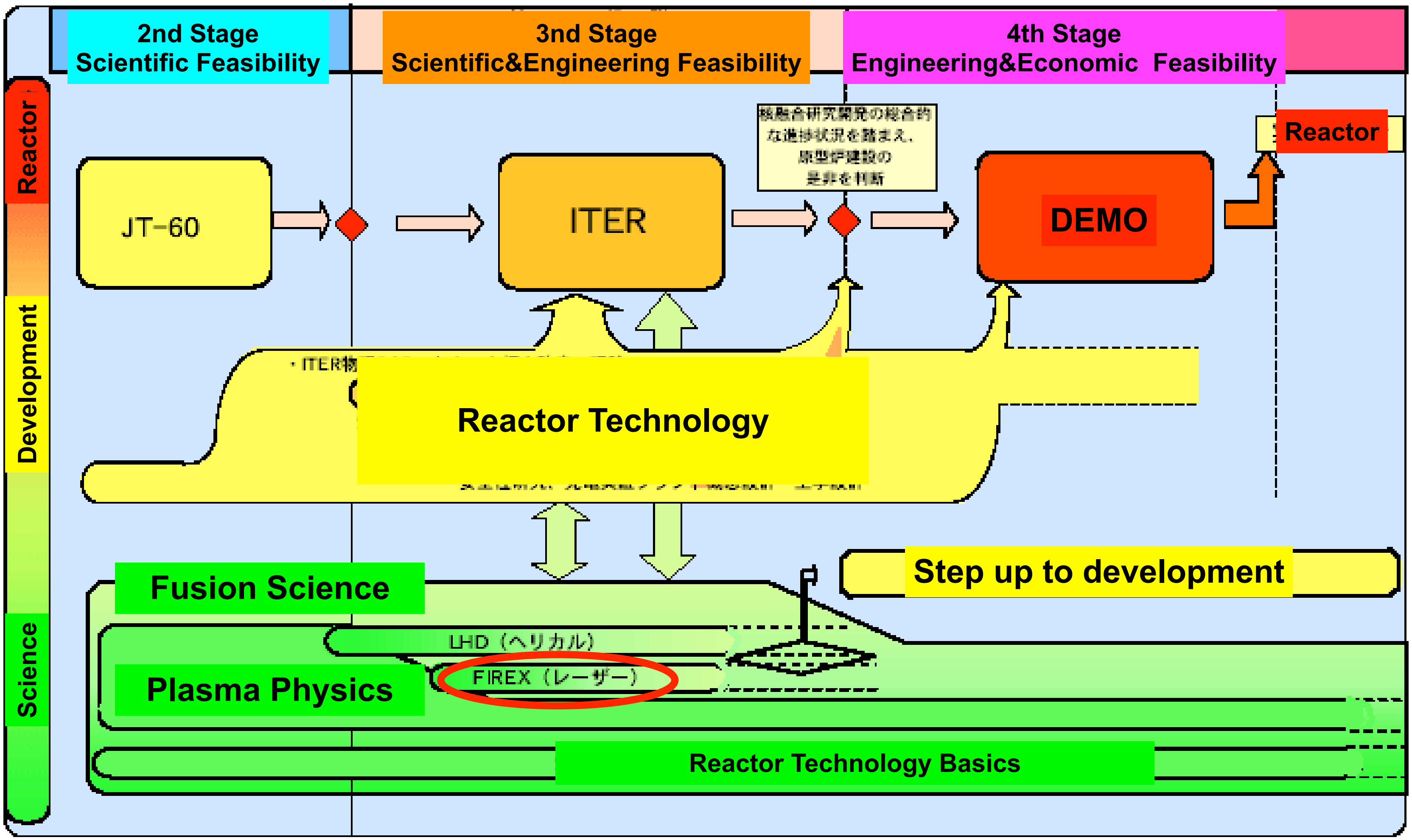


IFMIF, Tokamak, LHD, Laser have become the Centralized Facilities.
Start of FIREX-II will be judged based on the FIREX-I result.
(Atomic Energy Committee October 2005.)

Japan Atomic Energy Committee Report, Oct. 2005



- Tokamak is the primary development program.
- Helical or Laser will be selected as a secondary development program.

Problems to be overcome to conduct FIREX-II

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- Not many people do.

  -Reorganization from Fusion-Only Lab to National Users Facility to attract talented people in this field.

  -Organizing an International training system

- Too large as a single university program.

  Closed cooperation with major national labs.

Intense Lasers as Tools of Basic Science

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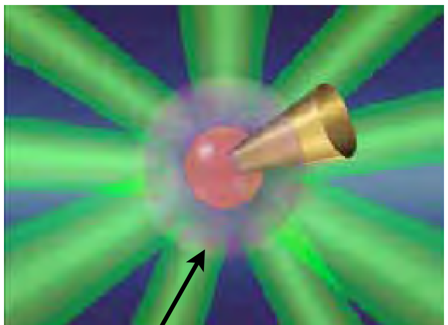
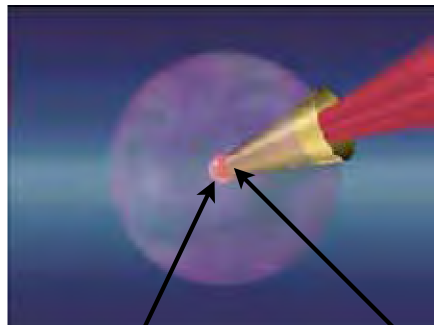
Implosion **Fast Heating** **Ignition/Burn** ########## ( )





1 mm size
100 Mbar

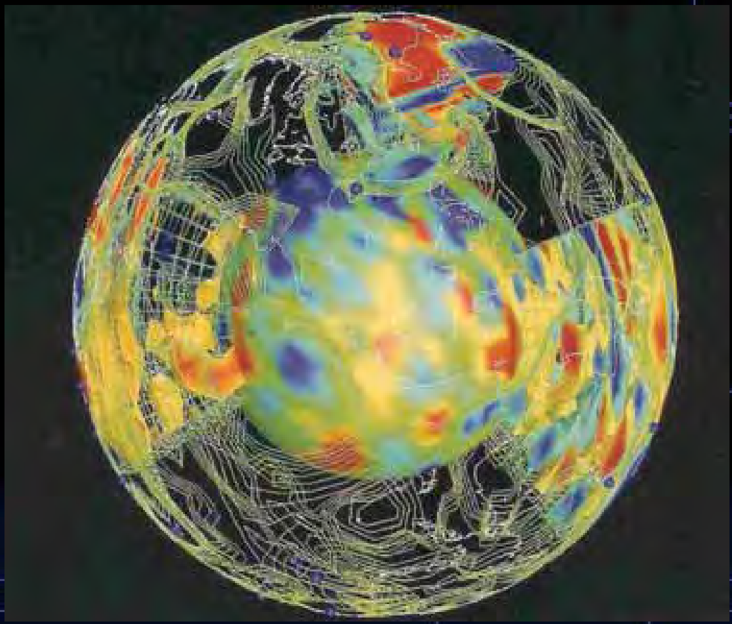
1/30 mm size
100 Mbar×$30^3 \approx$ 1 Tbar

Balanced light pressure
E field = 1 TV/cm =10 kV/Å

High Pressure **High Field**

地球の内部状態を得るための唯一の観測的情報は地震波データである

Hanshin-Awaji Earthquake, 1995



3D mantle tomography model “EHIME”
by GRC and CITE, Ehime University

Potential Industrial Use of High-Power Lasers

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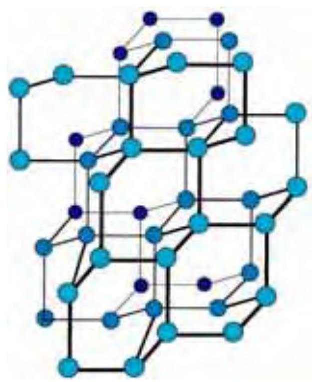
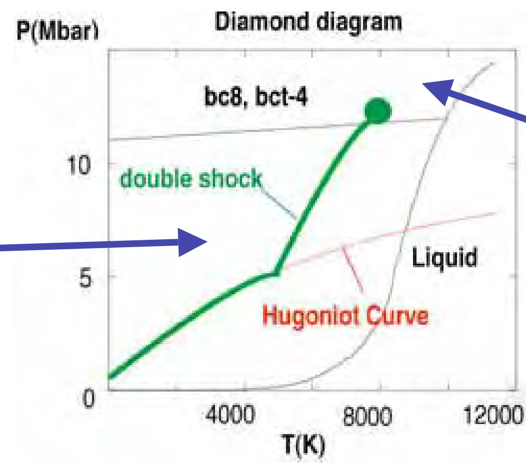
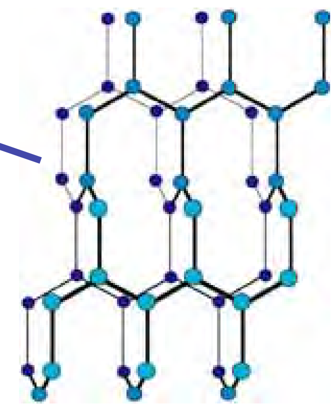
Diamond Structure







bct-4 Structure

- **Several meg companies to start the Industrial Use Program.**
- **5 mega companies, 8 personnel to join in the Industrial Use Committee.**

Major national labs have started cooperative programs of FIREX-I and HEDP

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National Institute for Fusion Science

FIREX-I

A. Iwamoto
T. Mito
H. Sakagami
T. Ozaki
M. Isobe

PoC: T. Norimatsu

Japan Atomic Energy Agency, Kansai

Beam Generation

T. Tajima
T. Kimura
H. Daido
T. Kawachi
H. Kiriyama

PoC: H. Nishimura

National Astronomical Observatory

Astrophysics

E. Kokubo
K. Tomisaka
4 Oversee Organizations
many others

PoC: H. Takabe

International COE of Education & Research

based on 20 institutional agreements

Osaka University's 6 institutions

- Institute of Laser Engineering
- Graduate School of Engineering
- Graduate School of Engineering Science
- Joining and Welding Research Institute
- Center for Quantum Science and Technology under Extreme Condition
- Graduate School of Science

Relativistic Plasma
Extreme Quantum Beam

Radiation Hydrodynamics
Photon Factory

Ultimate Photonics and Applications

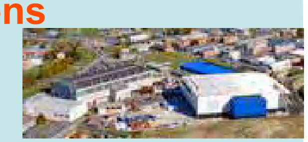
High Pressure Condensed Matter
New Materials

Osaka University Ultimate Photonics Asian Center\ （OPAC)

Japan Atomic Energy Agency-Kansai

Asian Institutions
China: 浙江大学 理学部
北京物理学研究所
上海光机所
Korea；韓国原研(KAERI)

US&EU Institutions
RAL/CCLRC
LULI
LLE/Rochester
Alberta
LLNL/UC



Summary

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- Based on the high-density compression and efficient heating, FIREX-I has started to demonstrate ignition temperature.

- Ignition and related results by FIREX-I, NIF, and LMJ will provide concrete basis of stating FIREX-II

- We need more people and more support:
  -Academic Use: National Users Facility.
  -Industrial Use: Government Supported Program.
  -Co-operative programs with major national labs

- International program: As a first step, international “system” to provide training and jobs for young talented graduates.

A-side: Thirteenth beam shoots a fuel.
FIREX and NIF appear in the longest-life cartoon GOLGO 13, a serious sniper story.

Osaka-FIREX

Livermore-NIF

ゴルゴ13 第435話
小学館ビッグコミック2003.10.25&11.10

HiPER: the route to IFE in Europe

Mike Dunne

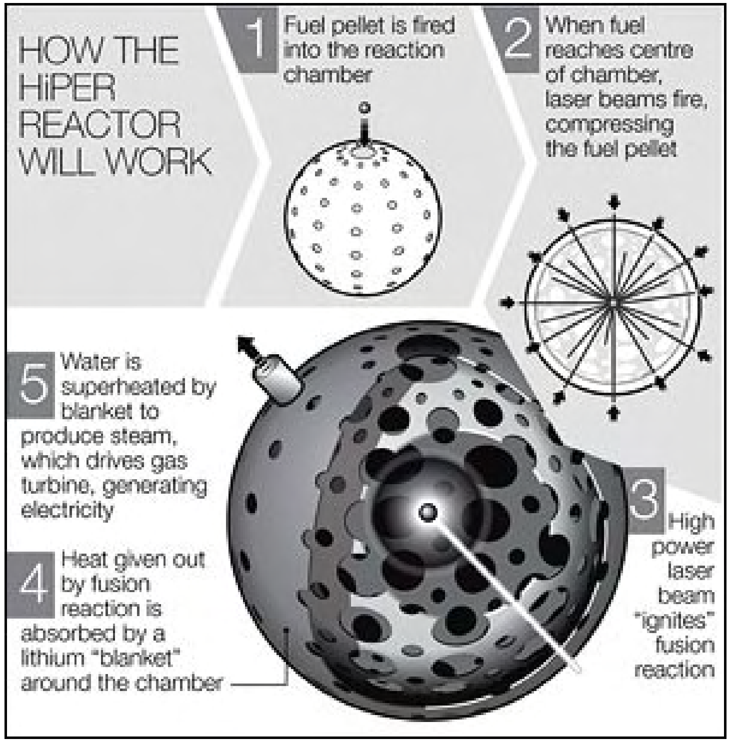
Director,
Central Laser Facility,
Rutherford Appleton Laboratory, UK

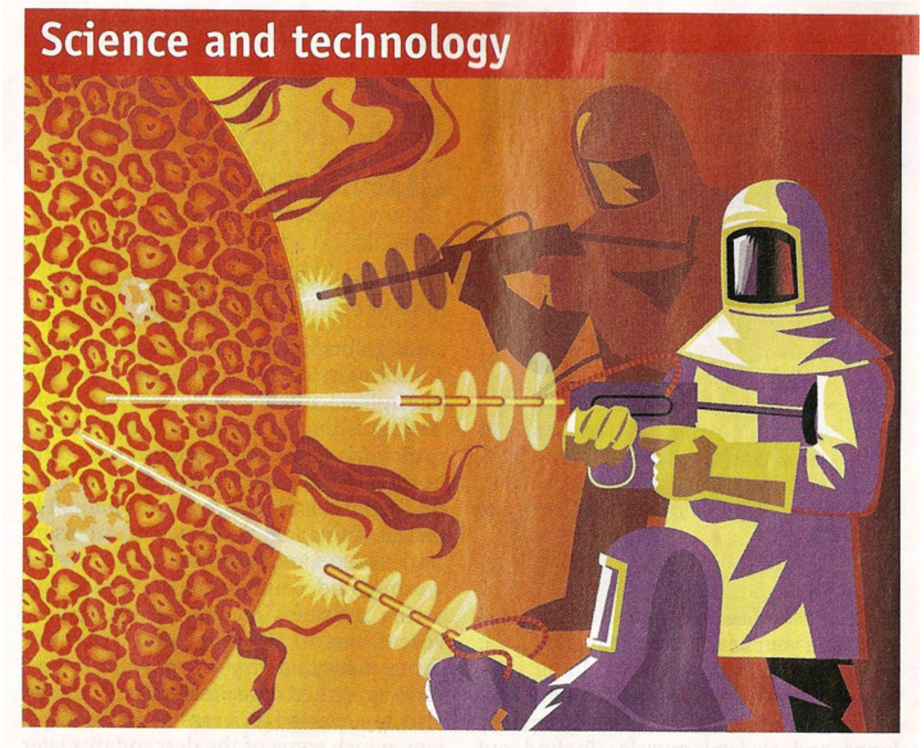
m.dunne@rl.ac.uk www.clf.rl.ac.uk www.hiper-laser.org

IFE viewed by the popular press …

Telegraph.co.uk

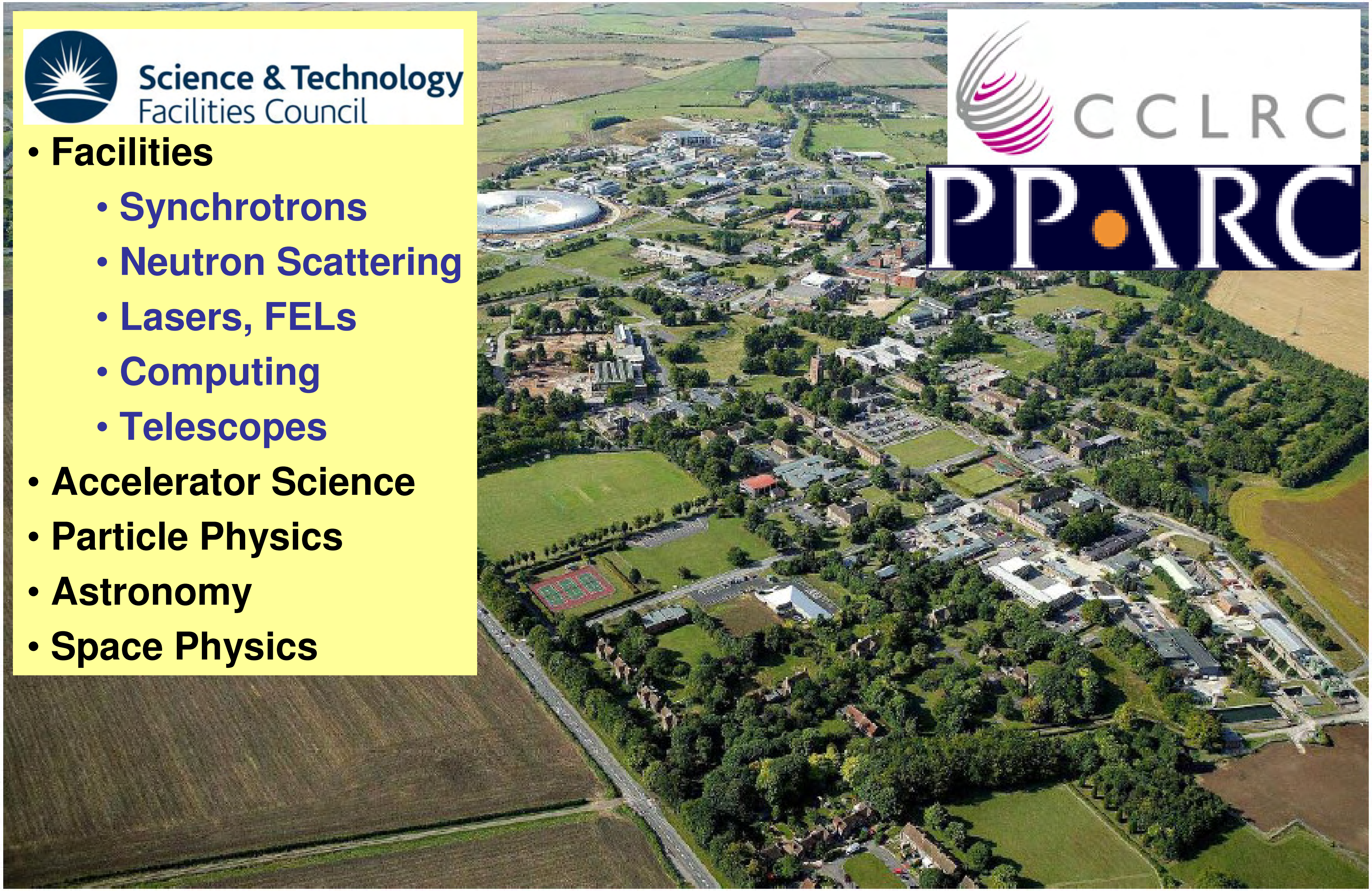
The Economist





Some observations from an outsider …

- Given the impressive history and levels of fusion investment within the USA, the lack of a coherent strategy beyond ignition is striking
  - This workshop process is much needed.
- Must plan on success. Clear response to the transformational event
  - Politicians and the public are impatient and fickle. So start now.
- We need to transition **from** salesmen of local programmes **to** advocates for fusion as a societal endeavour
  - National, focused efforts. International cooperation.
- Obviously work within political constraints, but be fully aware of the impact of research choices on the long term goal
- One major lesson for me from the past year of European integration:
  - Technical issues are only a small part of the effort. Need to address: public understanding, policy alignment, commercial positions, legal and governance issues, industrial impact, financial modelling, etc etc etc
  - These are as much **our** problems as the technical issues. Who else?
- **Watchwords**: Cooperation, Coordination, Coherence, Credibility



Science & Technology Facilities Council

CCLRC

PPARC

- **Facilities**
    - **Synchrotrons**
    - **Neutron Scattering**
    - **Lasers, FELs**
    - **Computing**
    - **Telescopes**
- **Accelerator Science**
- **Particle Physics**
- **Astronomy**
- **Space Physics**

The European Laser Community

Laserlab Europe

- **Trans-national access**
- **Joint technology development**
- **Coordinated strategic goals**

plus:
European training programs

18 European Laser Laboratories

HiPER

EC science funding

SEVENTH FRAMEWORK PROGRAMME

€53 Billion ($70B) / 7 years for international research & development

This is intended to be coordinating & catalytic, to leverage national science funds

• Cooperation	€ 32 B	(joint projects)
• Capacities	€ 4 B	(new facilities)
• People	€ 5 B	(training & mobility)
• Ideas	€ 7 B	(research projects)
• also : Euratom	€ 2.7 B	(fusion)

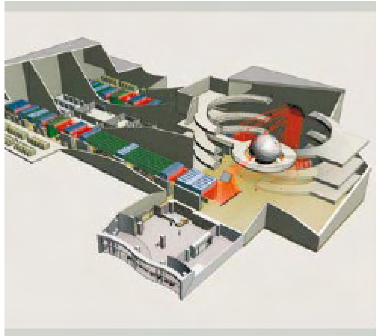
HiPER European Roadmap for new Facilities

- 35 "Opportunities"
- Dedicated EC funding for design
- Construction via European Govts

HiPER

The facility

HiPER will be a large scale laser system designed to demonstrate significant energy production from inertial fusion, whilst supporting a broad base of high power laser interaction science. This is made feasible by the advent of a revolutionary approach to laser-driven fusion known as "Fast Ignition". HiPER will make use of existing laser technology in a unique configuration, with a 200 kJ long pulse laser combined with a 70 kJ short pulse laser.



Background

High power lasers enable the physics of matter at extreme densities and temperatures to be studied in the laboratory, with applications ranging from fundamental science, to new technological opportunities (e.g. compact particle accelerators and laboratory based astrophysics) and high impact industrial exploitation (e.g. inertial fusion energy).

Energy production from Inertial Fusion was proven in the 1980s, with laser driven inertial fusion due to be demonstrated in the laboratory in the period 2009-2012. To date, however, research in inertial fusion has been limited to the defence sector due to the scale of the laser facilities needed to initiate the process. The advent of Fast Ignition completely changes the landscape, removing the dependence on defence programmes, using a method which breaks the scientific link of radiation driven implosions. Construction of HiPER would allow Europe to lead the world in this field, taking advantage of these transformational events.

**What's new?
Impact foreseen?**

The technique of "Fast Ignition" is a revolutionary approach to inertial fusion, calculated to lead to an order-of-magnitude reduction in the scale (and thus cost) of the laser facility. Recent demonstration experiments have been published in a series of articles in Nature and have led to the 2006 American Physical Society award for Excellence in Plasma Physics. The unique laser configuration creates the opportunity to provide a world-leading, broad-based research infrastructure in Europe. This type of laser fusion facility will open up a wide range of applications in laboratory astrophysics, nuclear physics, atomic physics, plasma science and material studies under extreme conditions.

Timeline and estimated costs

Based on the ongoing conceptual design work and experience with LIL-PETAL, the construction cost of the facility is estimated at ~800 M€, with a preparatory cost of ~55 M€ (including completion of PETAL), and an annual operating cost of ~80 M€. The present scientific and technological basis of the facility allows a 3-year detailed design phase to start immediately, with construction envisaged

Why now for a European IFE programme?

- Demonstration of ICF ignition within ~ 3 - 5 years
- Public & political visibility of fusion via ITER, NIF, LMJ, IFMIF

- **We need to position ourselves to take full advantage of these fundamental step-changes in our field**

- **International cooperation will be essential**
  (technology development & science programmes)
  - Staged approach (existing facilities → PETAL → HiPER)
  - Underlying research (plasma physics, targets, modelling …)

- **Parallel development of IFE building blocks is strategically necessary**
  - High gain facility; Future IFE reactor design
  - High repetition rate driver; Mass target production

An international project

Expected partners in the preparatory phase (at the ministerial / national funding agency level):

UK, France, Spain, Italy, Portugal, Czech Republic, Greece

Other partners in the preparatory phase (at the institutional level):

Germany, Poland, Russia

International links:

USA, Japan, China, South Korea, Canada

Included on European roadmap (Oct 06)

UK endorsement – coordinators (Jan 07)

Bid for next phase (EC+MS) (May 07)

HiPER European Preparatory phase project

3 year project with 3 main deliverables:

1. Design of the HiPER facility (options)
2. Mobilising the European laser/plasma community
    - Integrated modelling capability
    - Integrated experimental programme
    - Confidence in the Fast Ignition parameters
    - Readiness of IFE technology
    - Coordination with international partners
3. Legal, financial and governance framework

Result:

Provide the basis for a political decision to proceed (“signature ready” formal Agreement)

Scale of the 3-year preparatory project

> 50 M€ committed to HiPER by the project partners

EC contribution to be determined after proposal submission (2 May 07)

DRAFT

HiPER

Progress towards a common approach

- **Re-direction** of existing programmes to be dedicated to the successful realisation of HiPER
- **Identification** of new resources to this project at the national and regional government level
- **Coordination** of user access to the three highest energy European laser laboratories (CLF, LULI, PALS)
- **Alignment** of all the major high power laser groups within Europe to define a common plan.
- **Cooperation** with International partners being pursued: USA, Japan, Canada, South Korea, China
  - Concepts, experiments, training, component supply, …

Staged approach towards HiPER agreed

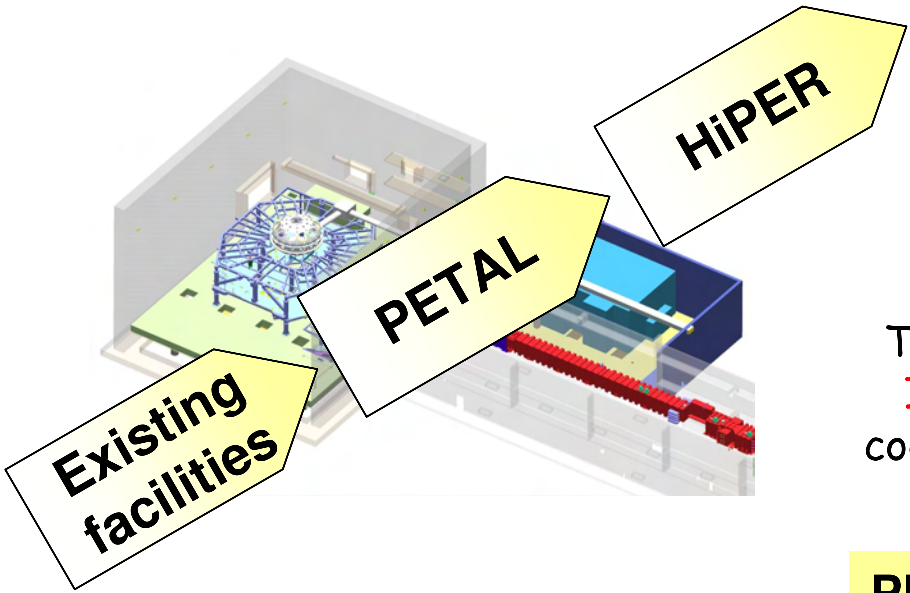
A single approach to IFE within Europe has been defined

Common strategic theme, with phased facility development:

– PETAL: Integration of PW and high energy beamlines

– HiPER: High yield facility

Coordinated scientific and technology development between the major European laser laboratories (e.g. Vulcan, LULI, PALS, …)



3.5 kJ	60 kJ
0,5 – 10 ps	8 beams
Up to 7 PW	ns , 3ω

The PETAL scientific program is under the Institute Lasers and Plasmas (ILP) which coordinates high intensity lasers activities in France

PETAL operational 2009 (60kJ + HEPW)

The intention:

- International scale laser to develop a route to affordable IFE
- Science flexibility is essential – to deliver fundamental research programme
- Needs to offer a unique, competitive capability.
- Needs to be an civilian, academic facility
- FAST IGNITION approach chosen to meet these criteria
  - Scope set to allow multiple FI options
  - Scale set to produce robust high gain

Options for the next step

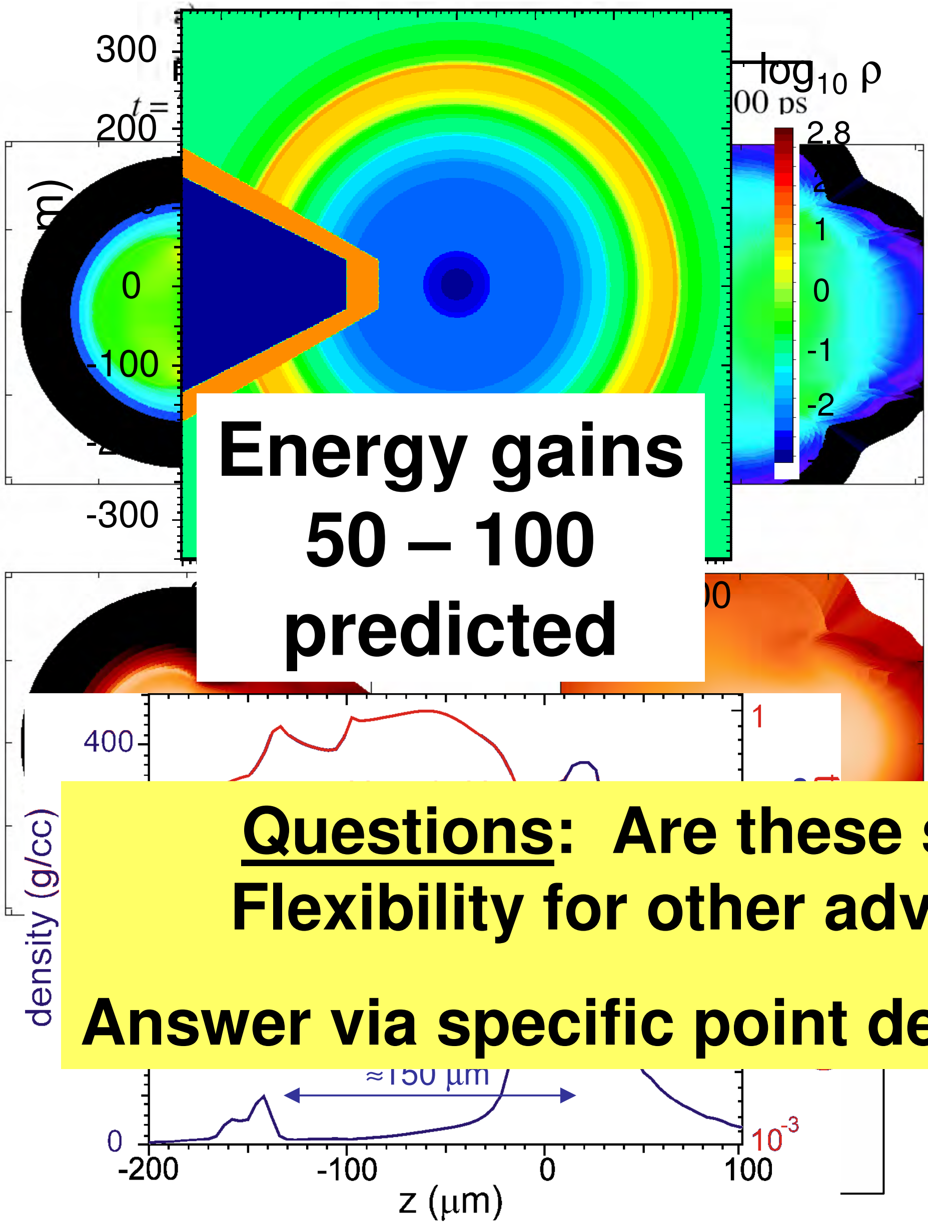
- Full scale, high rep-rate fusion facility
- High yield (fast ignitor) demonstrator

Both options to be analysed to allow an informed decision

HiPER Flexibility for a broad science programme

- **Material Properties under Extreme Conditions**
  Unique sample conditions & diagnosis
  Non-equilibrium atomic physics tests
- **Laboratory Astrophysics**
  Viable non-Euler scaling & diagnosis
- **Nuclear Physics**
  Access to transient & obscure nuclear states
- **Neutron Scattering**
  PoP for IFE based neutron scattering source
- **Turbulence**
  Onset and evolution in non-ideal fluids
- **Radiation transfer and HED physics**
  Unique sample conditions & diagnosis
- **Development of new particle beam sources**
- **Fundamental strong field science**

HiPER Specification based on initial modelling



Energy gains 50 – 100 predicted

Analytical scaling laws

2D radiation hydrodynamic Implosion simulations

3D hybrid kinetic models of electron transport

<u>Questions</u>: Are these simulations believable?
Flexibility for other advanced ignition options?

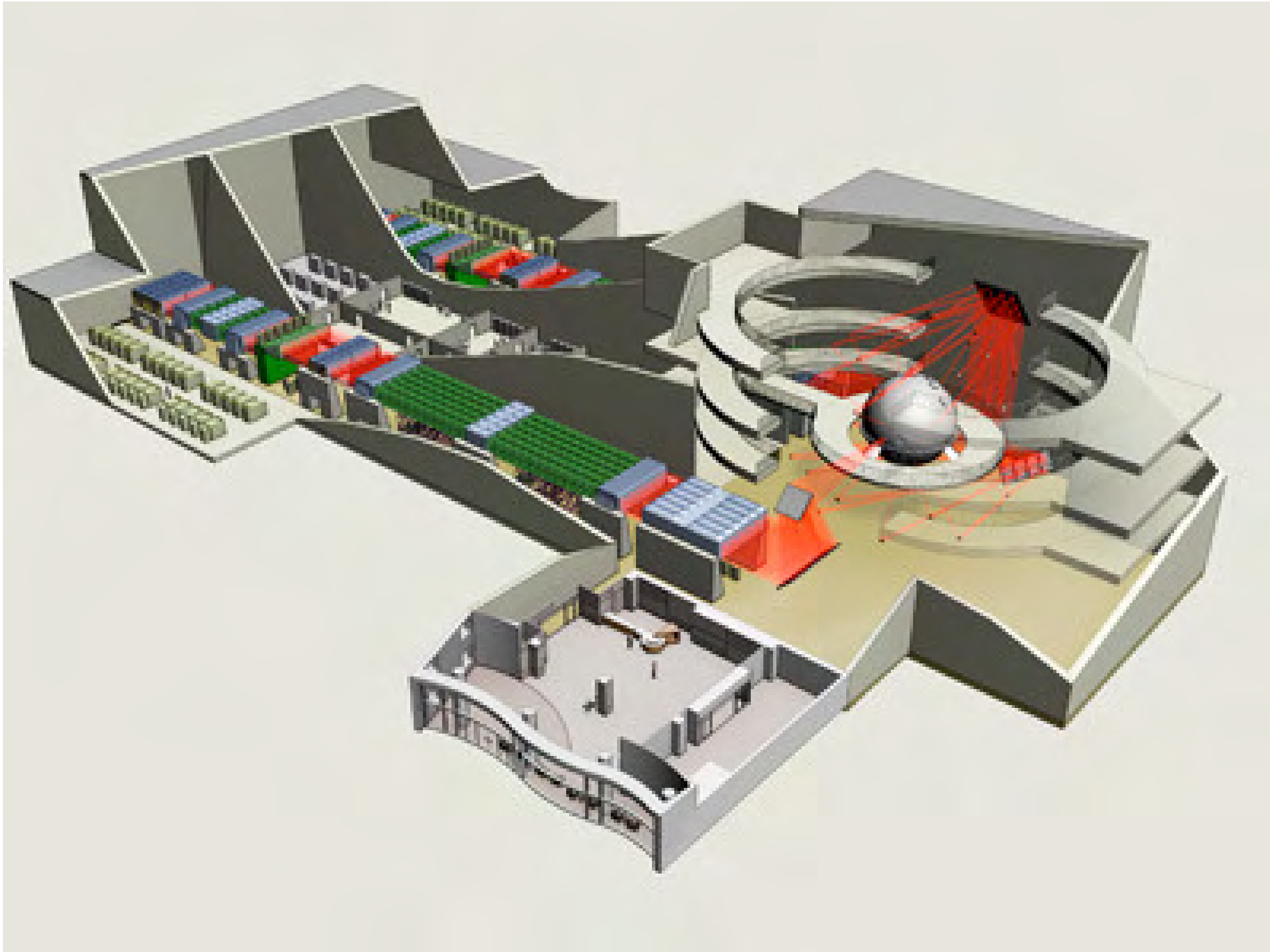
Answer via specific point designs on integrated facilities

Baseline specifications

1. **Implosion energy:**
   200 kJ in 5ns
   10 m chamber
   2ω or 3ω?

2. **PW beamlines:**
   70kJ in 10ps
   2ω (how?)

3. Parallel development of IFE building blocks
- **Target manufacture**
- **DPSSL laser**
- **Reactor designs**



4. Future OPCPA options to provide 150 PW beam (probe) and/or 2 EW (driver)

5. Enhanced support infrastructure & cooperation required throughout Europe

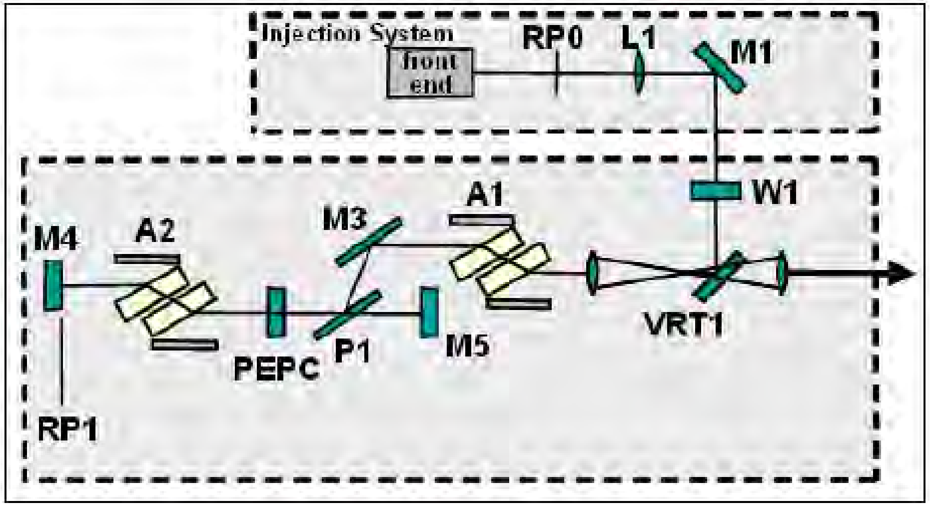
HiPER High Average Power Laser development

Progress is needed prior to the decision to construct

- 1 kJ / 10 Hz or 10 kJ / 1 Hz options assessed
- Workshops with research groups + industry (Chanteloup, Paris, Nov 06)

HAPL on HiPER

- Degree of implementation?
- Independent beam to be used for:
  - diagnostic & laser technology development
  - coupled sources (with accelerator)
  - fusion chamber material science (high average flux)



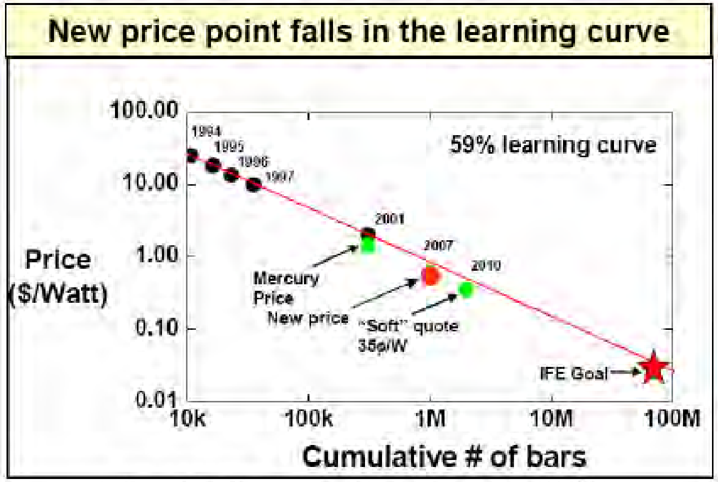


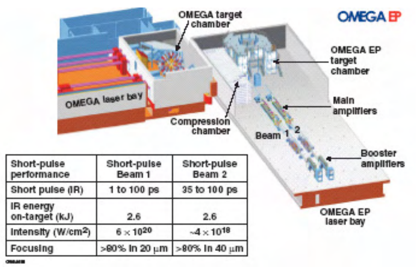
Figure 6.3 : LLNL estimation for diode bar cost evolution [8].

International cooperation

1. **Lessons from emerging generation of facilities** (FIREX, EP, …)

2. **Activities to ensure growth of the European laser community**
   - via national and other international projects
   - via Laserlab-Europe I3.

3. **Coordination with other international partners**
   - Russia, Japan, S Korea, China, Canada, USA, …
   - Trans-national governance framework ?
   - Common long term demonstrator ??



Short-pulse performance	Short-pulse Beam 1	Short-pulse Beam 2
Short pulse (IR)	1 to 100 ps	35 to 100 ps
IR energy on-target (kJ)	2.6	2.6
Intensity (W/cm^2)	6×10^{20}	$\sim 4 \times 10^{18}$
Focusing	>80% in 20 μm	>80% in 40 μm

2007 OMEGA EP laser, USA
5.2kJ PW + 30kJ $3\omega_0$

2007 FIREX-I laser Japan 10kJ PW + 10kJ $2\omega_0$
FIREX-II: 50kJ + 50kJ

Required technical developments

- Improved understanding of the target performance
  - Needs coordinated research programs on international laser facilities
  - Point design assessment, and key physics issues
- Laser design
  - HEPW, OPCPA, 2ω/3ω options,
  - High repetition rate, high efficiency drivers
- Micro-fabrication & delivery of fuel pellets (and future bulk manufacture methods)
- Integrated reactor designs

International cooperation in these areas is essential

HiPER

Conclusions

- We are entering a new era for Fusion Energy
- A concept for a next-generation European facility has been proposed
- Includes significant development of laser, target and code capability
- Included on national & European roadmaps
- Next stage is detailed facility design – needs coordinated, international approach

IAEA Coordinated Research Project on IFE

Neil B. Alexander

Inaugural IFE Science and Technology Strategic Planning Workshop:Updates on Progress, Visions, and Near-Term Opportunities

San Ramon, CA
April 24-27, 2007

GENERAL ATOMICS

This series of CRP's could be used to spring-board a large scale international IFE effort

- **IAEA is about sharing nuclear information for peaceful purposes**

- **IAEA can provide a framework and a context for international collaboration**
  - Even for large facility

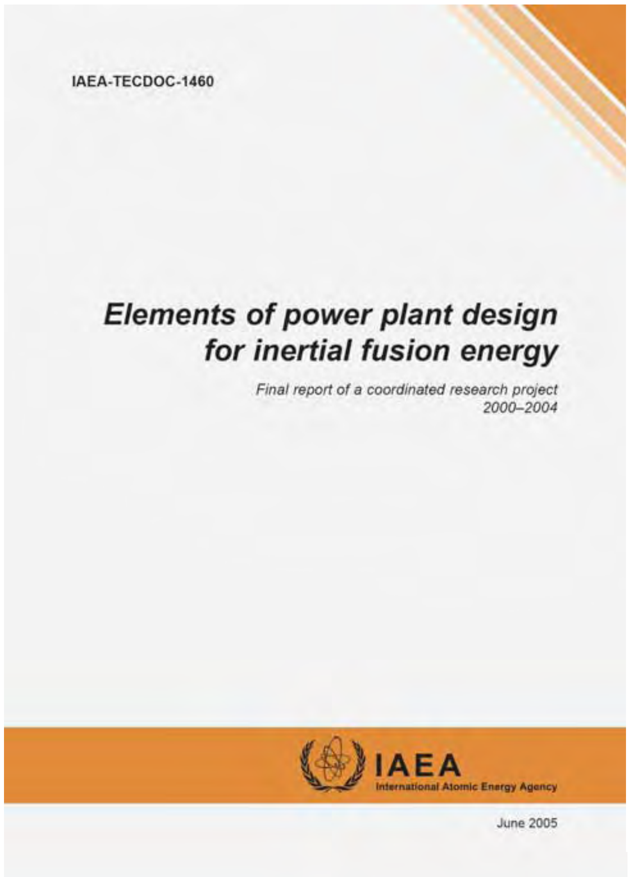
The IAEA has started a series of Coordinated Research Projects (CRP) on Inertial Fusion Energy

- **The initial IFE CRP was "Elements of Inertial Fusion Energy (IFE) Power Plants"**
  - Ended 2005
  - Ran ~4 years
- **The 2nd and current CRP (F1.30.11) is "Pathways to Energy from Inertial Fusion – An integrated approach"**
  - Began 2006, should run ~4 years
  - 1st Research coordination meeting (RCM) Nov 11, 2006, Vienna
- **A similar series of CRP's was a prelude to ITER**

The initial IFE CRP sought to develop pieces needed for IFE reactor

- CRP to help introduce IFE researchers from member states
- Initial CRP output is available in IAEA TecDoc's

IAEA-TECDOC-1460

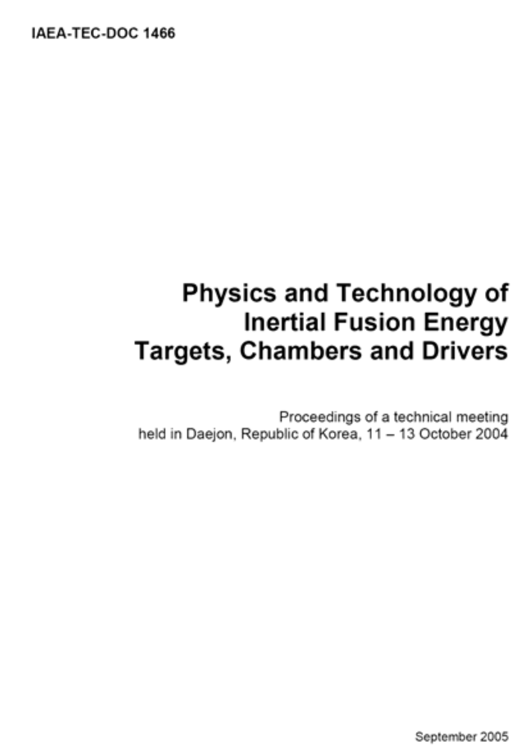

IAEA-TECDOC-1460

Elements of power plant design for inertial fusion energy

Final report of a coordinated research project 2000–2004

IAEA
International Atomic Energy Agency

June 2005


IAEA-TEC-DOC 1466

Physics and Technology of Inertial Fusion Energy Targets, Chambers and Drivers

Proceedings of a technical meeting held in Daejon, Republic of Korea, 11 – 13 October 2004

September 2005

IAEA-TECDOC-1466

There were many participants in initial IFE CRP

Földes, I.	KFKI	Hungary
Goodin, D.	General Atomics	U.S.A.
Hoffmann, D.	GSI Darmstadt	Germany
Izawa, Y.	ILE Osaka Univ.	Japan
Kálal, M.	Czech Tech. Univ.	Czech Republic
Kasuya, K.	Tokyo Inst. Tech.	Japan
Kato, H.	Gifu University	Japan
Kawashima, T.	ILE Osaka Univ.	Japan
Kaydarov, R.	Nat. Univ. Uzbekistan	Uzbekistan
Kong, H.J.	KAIST	Korea
Koresheva, E.R.	Lebedev Physical Inst.	Russian Federation
Lee, B.-J.	KBSI	Korea
Lee, S.-K.	KAIST	Korea
Lim, C.	KEARI	Korea
Mank, G.	IAEA	
Matsumoto, O.	ILE Osaka Univ.	Japan
Meier, W.R.	LLNL	U.S.A.
Nakai, S.	Koichi Nat. Coll. of Tech.	Japan
Norimatsu, T.	ILE Osaka	Japan
Perlado, J.M.	DENIM UPN	Spain
Rudraiah, N.	NIRAM	India
Sharkov, B.Y.	ITEP	Russian Federation
Skoric, M.M.	VINCA	Serbia and Montenegro
Tillack, M.S.	UCSD	U.S.A.
Wolowski, J.	IPPLM	Poland
Ying, A.	UCLA	U.S.A.

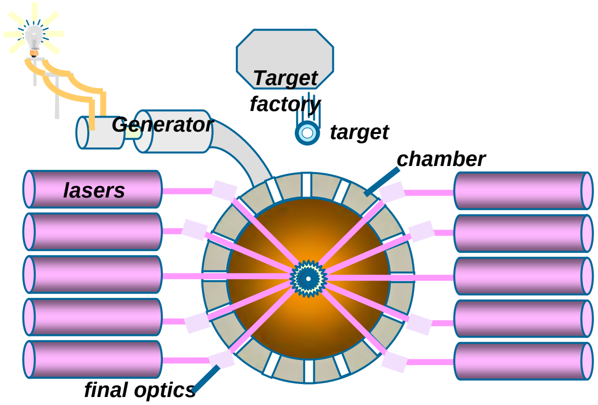
Current CRP also has many participants

- This CRP starts to build international collaboration through integrated approaches

Alexander, N. B.	General Atomics	U.S.A.
Desai, T.	NRIAM	India
Földes, I.	KFKI	Hungary
Hoffmann, D.	GSI Darmstadt	Germany
Kálal, M.	Czech Tech. Univ.	Czech Republic
Kasuya, K.	Tokyo Inst. Tech.	Japan
Kaydarov, R.	Nat. Univ. Uzbekistan	Uzbekistan
Kong, H.J.	KAIST	Korea
Koresheva, E.R.	Lebedev Physical Inst.	Russian Federation
Mank, G.	IAEA	
Martin, W.	RAL	United Kingdom
Nakai, S.	GPI	Japan
Perlado, J.M.	DENIM UPN	Spain
Piriz, A.R.	U. de Castilla-La Mancha	Spain
Raffray, R.	UCSD	U.S.A.
Sharkov, B.Y.	ITEP	Russian Federation
Shmatov, M.	Ioffe	Russian Federation
Tikhonchuk, V.	Inst. Lasers and Plasma	France
Wolowski, J.	IPPLM	Poland
Advising:		
Meier, W.R.	LLNL	U.S.A.

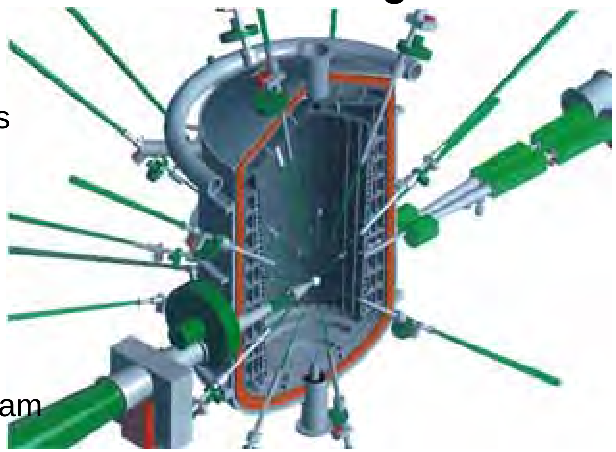
There are a number of integrated reactor concepts represented in the CRP

HAPL: Direct Drive



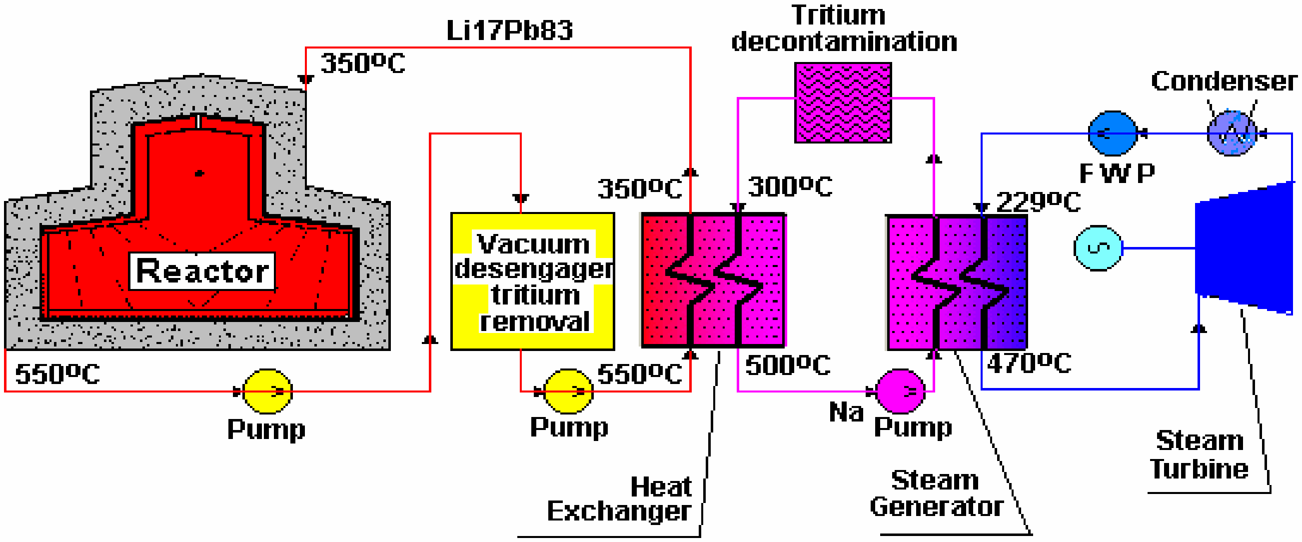
KOYO-F: Fast Ignition

Implosion beams



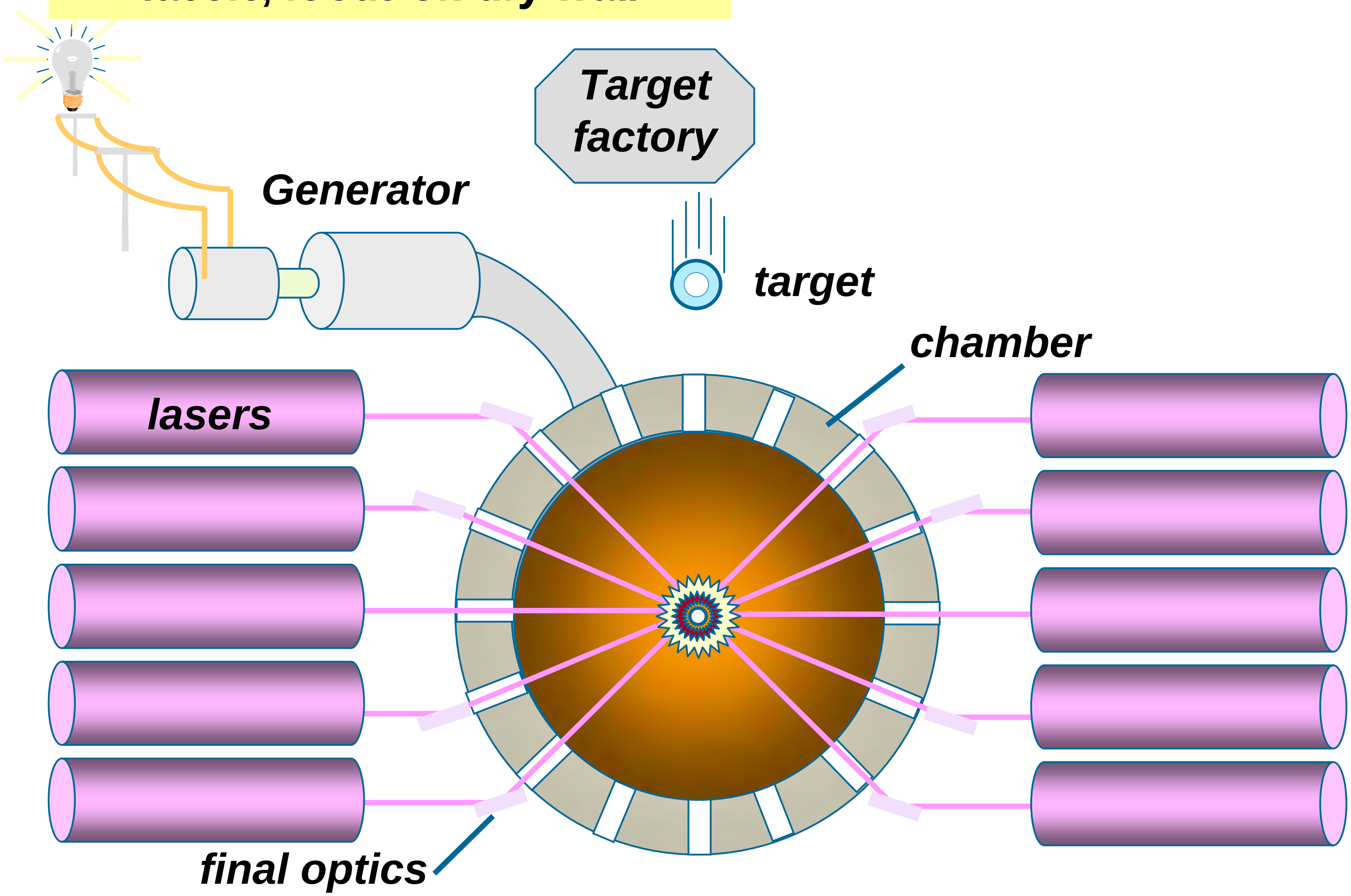
Ignitor beam

Heavy Ion with Fast Ignition

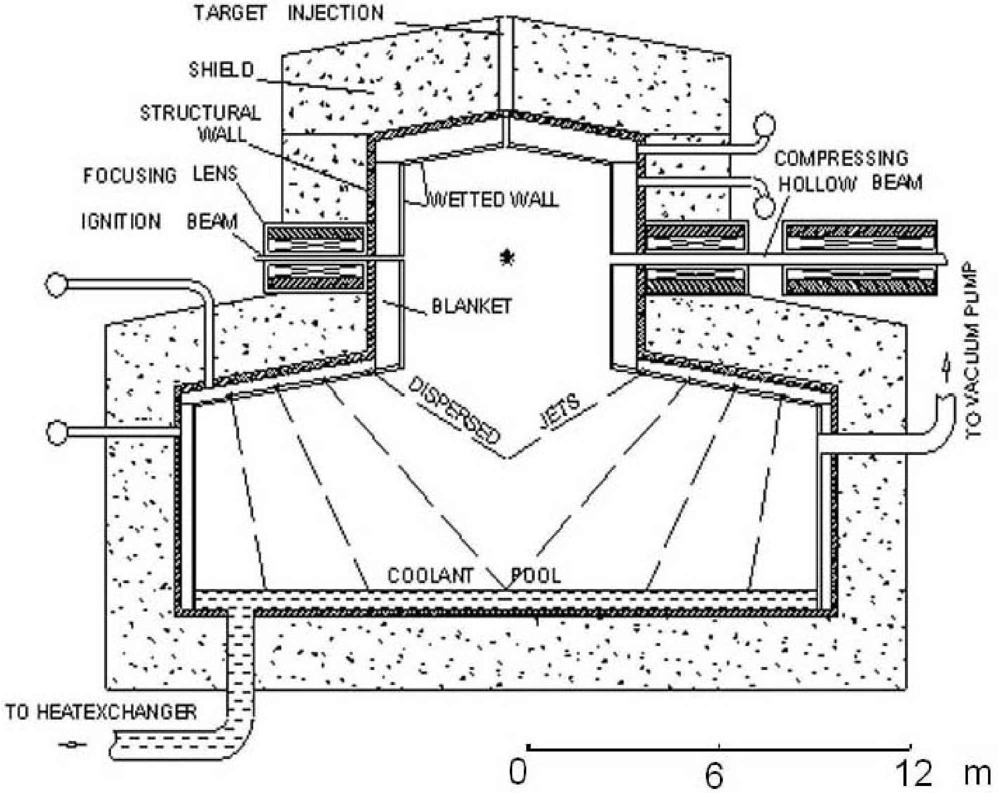


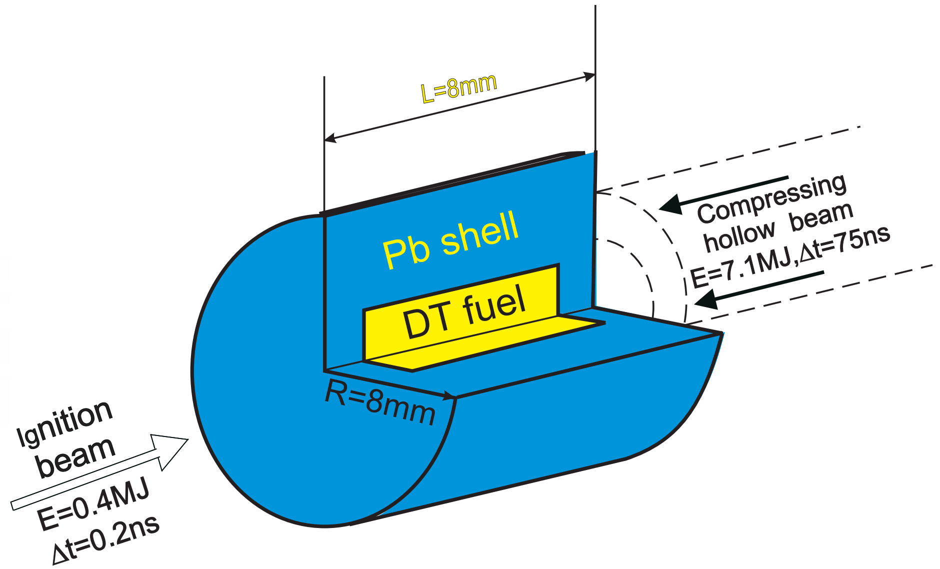
HAPL discussed earlier

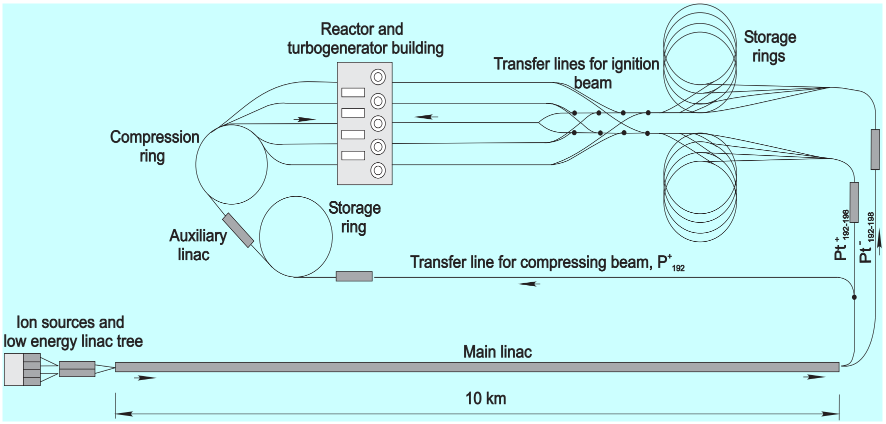
Primarily direct drive with lasers; focus on dry wall



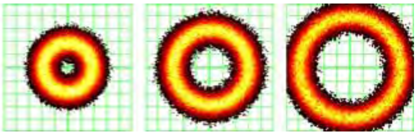
Fast ignition heavy ion reactor uses cylindrical targets





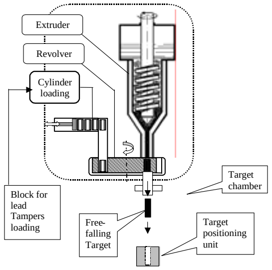


Heavy ion reactor is international collaboration



- **B.Sharkov (ITEP, Russia)**
  - System, target design, accelerator design, wobbler

- **D. Hoffmann, GSI Darmstadt (Germany)**
  - Experimental validation; 200-500 GeV/u, 4e9 U ions. Phelix laser with 2 NOVA MA + LLNL gratings 300TW

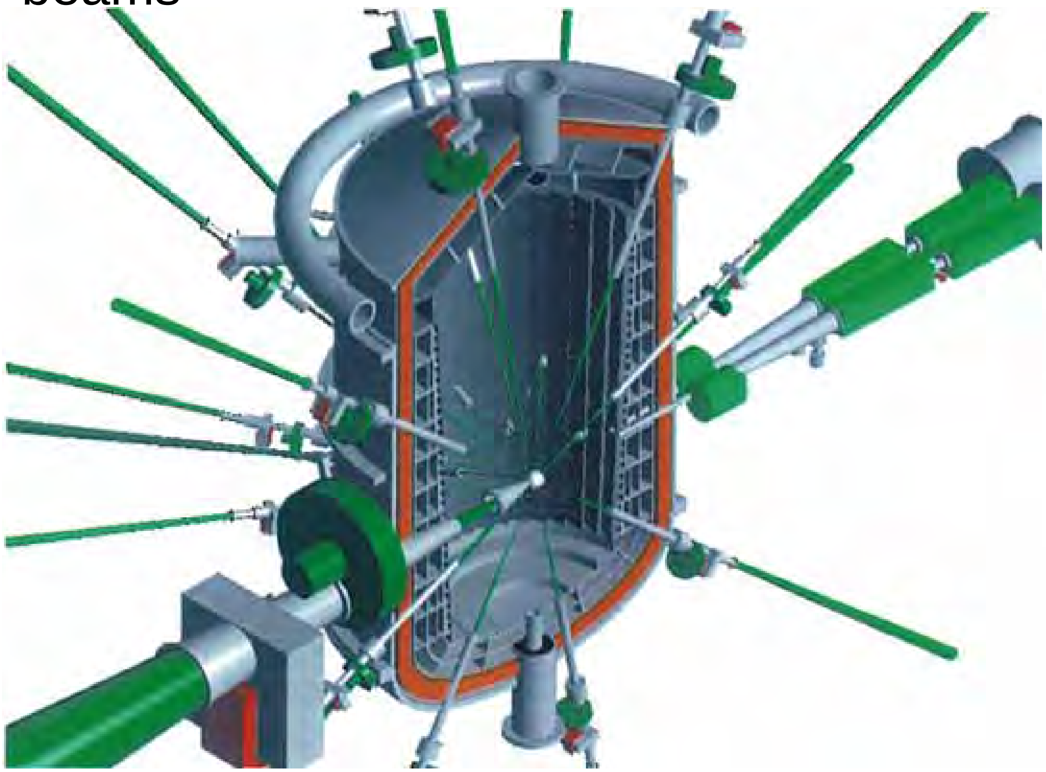


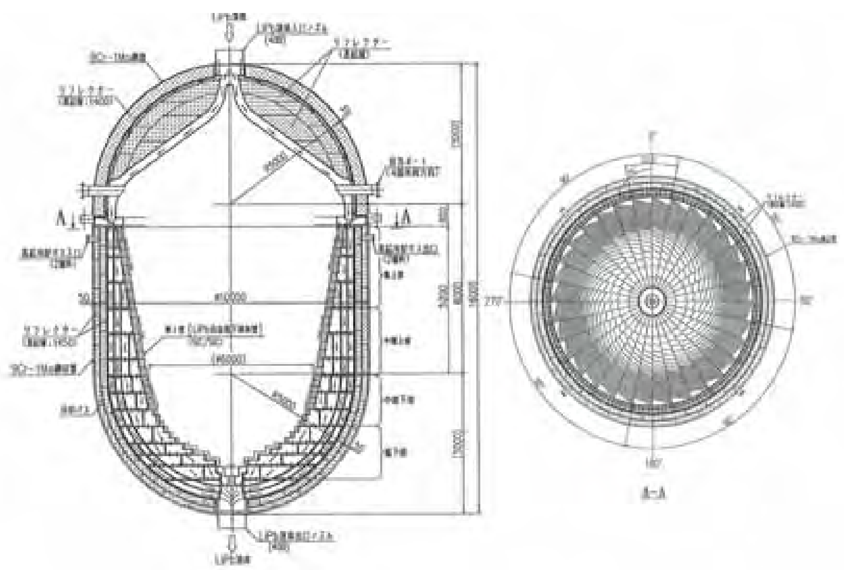
- **E. Koresheva, (LPI, Russia)**
  - Cryotarget
- **A. Piriz (UCLM, Spain)**
  - Hydrodynamic instability modelling and experiment
    - Z-pinch cap.'s from GSI; 700kA

- **R. Khaydarov (NUU, Uzbekistan)**
  - Ion sources

KOYO-F uses cone-in-capsule targets

Implosion
beams





Ignitor
beam

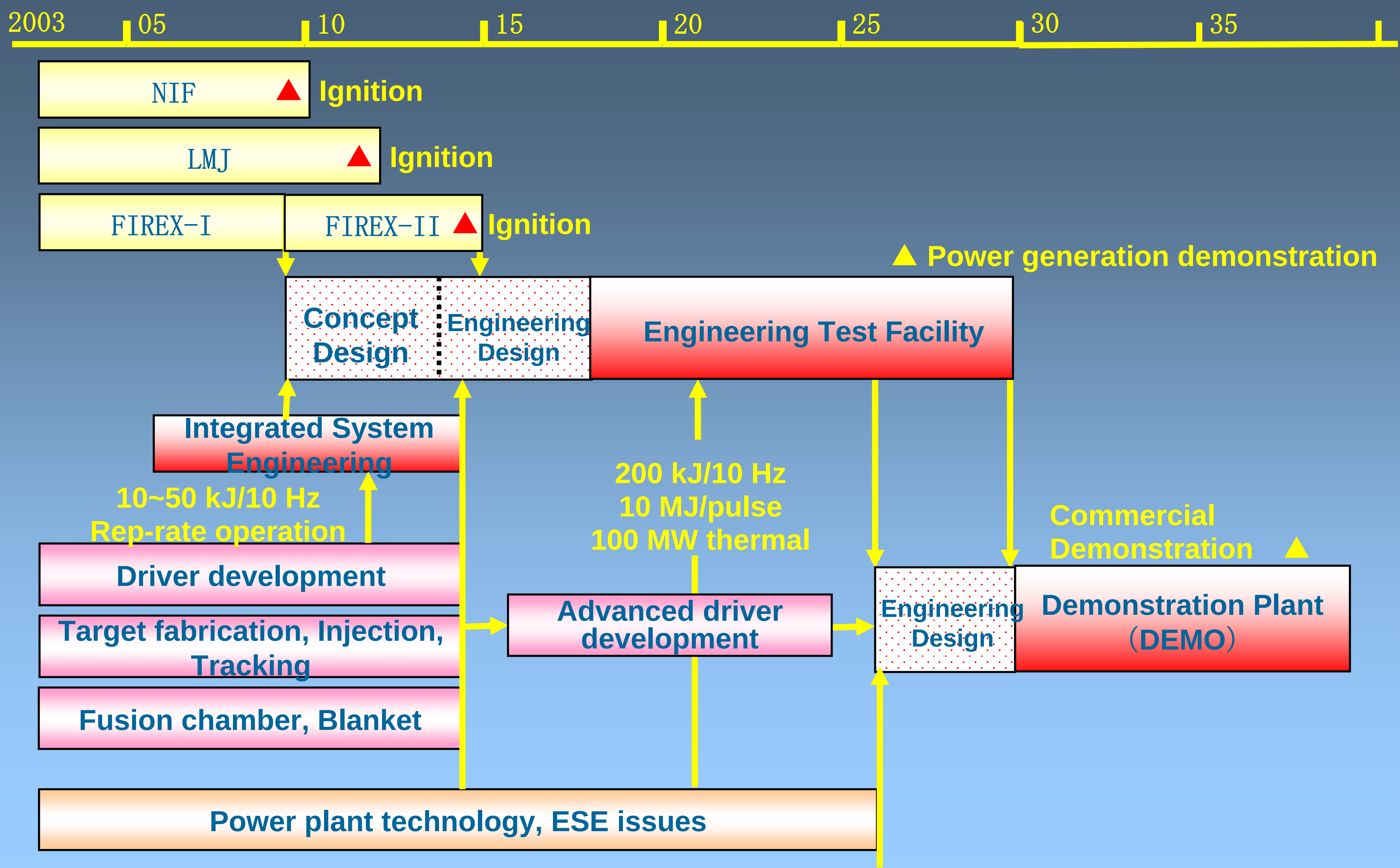
PbLi flowing through
weirs on walls

Angled to prevent
stagnation of blowoff on
axis

Japan has an integrated IFE program

Organization	Key Person	System	Driver	Chamber	Fuel	Application
ILE, Osaka University	K. Mima	○	○	○	○	○
Institute for Laser Technology	C. Yamanaka	○	○			○
The Graduate School for the Creation of New Photonics Industries	S. Nakai	○	○			○
Hamamatsu Photonics K. K.	T. Hiruma	○	○			○
Japan Atomic Energy Agency	Y. Kato	○	○			○
High Temperature Plasma Center, The University of Tokyo	U. Ogawa	○				
Central Research Institute of Electric Power Industry	K. Okano	○				
Kyoto University	S. Sakabe		○			
The University of Electro-Communications	K. Ueda		○			
University of Fukui	T. Kanabe		○			
National Institute for Fusion Science	Y. Kozaki	○		○	○	
Kyushu University	Y. Nakao				○	
Gifu University	H. Yoshida				○	
Hiroshima University	T. Endo				○	

Nakai showed power generation demonstation scheduled for 2027



Nakai suggested applications of intense neutron source as potential nearer term inertial fusion goal

(1) neutron engineering and transmutation

1-1 annihilation of radioactive waste of fissile fuel

1-2 isotope production

(2) blanket energetics

2-1 energy conversion, electricity and hydrogen production etc.

2-2 FNDS: the primary fusion neutrons initiate the secondary fission reactions in the under critical blanket

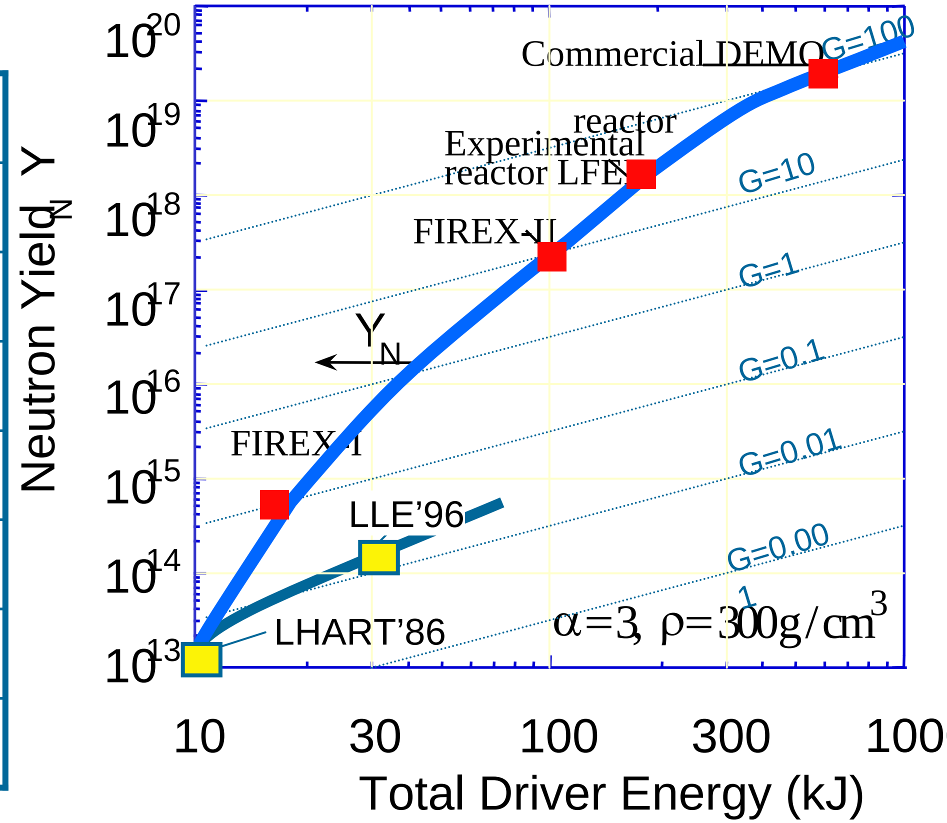
(3) fusion material irradiation facility

(4) medical application of neutrons such as Boron Capture Neutron Cancer Therapy (BCNT) , and

(5) miscellaneous application for radiation diagnostics of structures and materials

Intense neutron source could be based on proven LHART

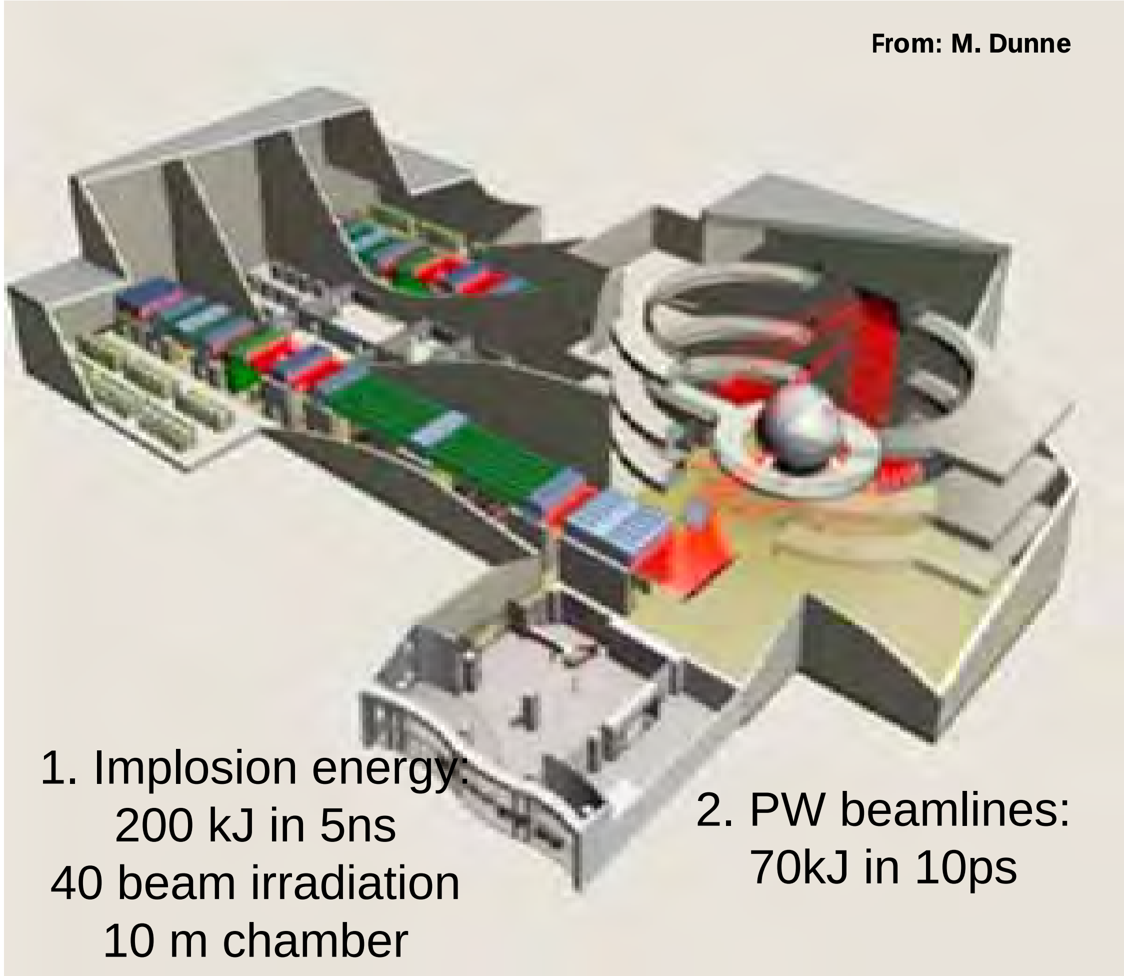
Physical Concept		Demonstrated	To be demonstrated
Beam target		10^5 / 100 J/ns	
Coulomb explosion		10^6 / 10 J/ps	
Implosion fusion	Exploding pusher	10^{12} / 10 kJ	
	LHART	10^{13} / 10 kJ~ 10^{14} / 30 kJ	
	Fast heating		10^{15} / 20 kJ
	Fast ignition		10^{18} / 200 kJ
	Central ignition		10^{19} / MJ



- **LHART: Large High Aspect Ratio Target**

The HiPER facility will have IFE as a main mission

- Civilian, fast-ignition based facility
- Described earlier by M. Dunne
- LIL Petal are coordinating with HiPER
- HiPER is an international collaboration
- CRP participants: CCLRC (UK), ILP (France), GSI (Germany), DENIM UPM (Spain), IPPLM (Poland), PALS (Czech Republic), GA (USA)
- Many other participants as well.

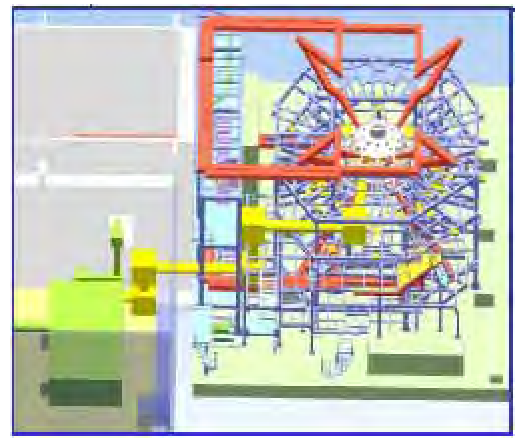


Other experimental facilities will be used by a number of participants

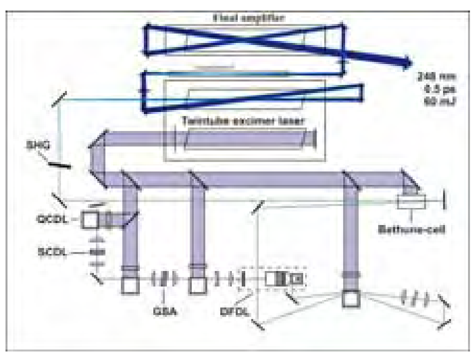
- **LIL +PW = Petal (France)**
- **PALS (Czech)**
- **HILL (Hungary)**
  - Short pulse KrF

8 beams, 60 KJ

3.5KJ, 0.5 - 10 ps

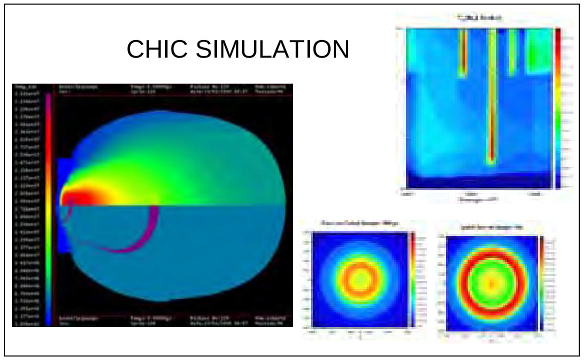


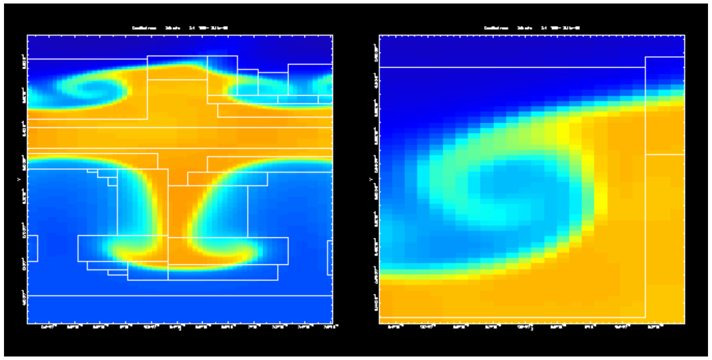
1KJ, >10^{16}W/cm^2

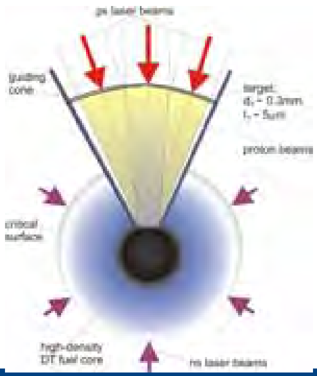


Modeling and theory for IFE are CRP activities

- ILP (France)
    - Target design codes
    - Direct Drive ignition studies for LMJ
- DENIM UPM (Spain)
    - Target design codes
    - Safety, accident assessment, environmental impact codes
    - Material properties/damage codes
        - multiscale
- IPPLM (Poland)
    - Investigate proton beam generation for FI by short pulse laser
    - Also exp.s on own laser, LULI and PALS

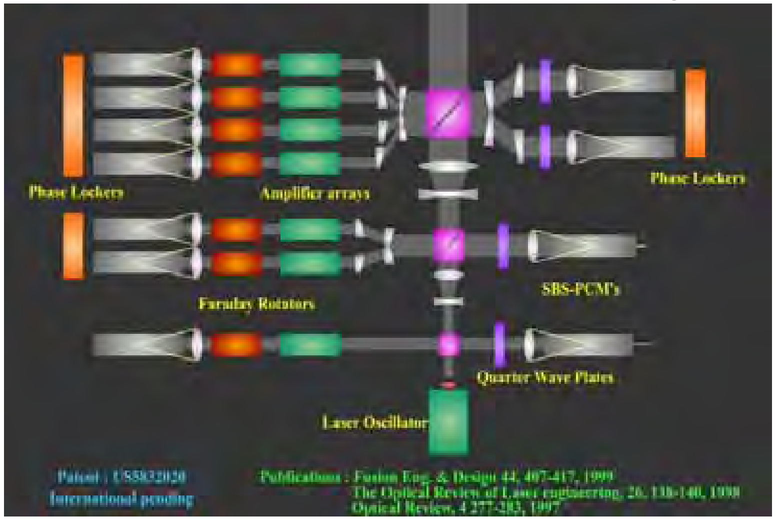




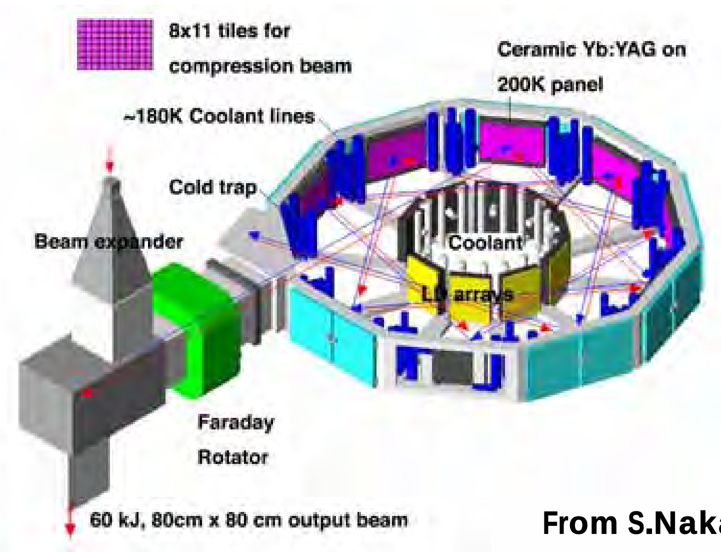


Strategic technology also part of CRP

From H.J. Kong, KAIST (Korea)



- **Fast ignition**
  - Get on a better gain curve
- **Rep-rated drivers**
  - Annular HI beam (corkscrew)
  - Phase conjugate mirrors for beam combination
    - Beat the heat using many small lasers
  - Cryogenic ceramic Yb:YAG laser
  - HALNA laser
- **Targets and Layering**
  - Solid layers: GA and LPI
  - Liquid in Foam: Japan
- **Injection and tracking**
  - Direct Drive: GA
  - Cone&Shell: Japan (Gifu U.)
- **Chamber walls**
  - Dry HAPL
  - Wet KOYO-F



From S.Nakai, GPI (Japan)

Paying attention to education of new IFE personnel was a recommendation of the meeting

- **From V. Tikonchuk (ILP, France)**

Long term operation of the both MCF and ICF large scale installations in France - ITER and LMJ requires a continuous influx of young researches

We are creating - opened in 2006 - a new formation **Master in the Science of Fusion** - common habilitation by 6 universities and 5 high schools all over the country with three proposed degrees:

master in the MCF - research
master in the ICF - research
master in the Fusion Technology - professional

Opened to the international community

The IAEA is promoting IFE via CRP's

- **There is international interest in IFE and it is growing**

- **International collaborations in IFE are starting to develop**

- **This and future IAEA CRP's can be used to motivate and promote future international IFE collaborations**

  Possibilities:
  - A rep-rated IFE prototype reactor?
  - An inertial fusion based neutron source?

- **Hope you got your abstract in for IAEA-TM embedded into IFSA07**
- **Thanks to Guenter Mank for initiating these CRP's**

UCRL-PRES-230753

A Survey of Advanced Targets for IFE

L. John Perkins
Lawrence Livermore National Laboratory

with thanks to: R.Betti, C.Zhou, K.Anderson, M.Tabak, S.Craxton, P.Bedrossian, S.Haan, R.Town, G.Logan, M.Murakami

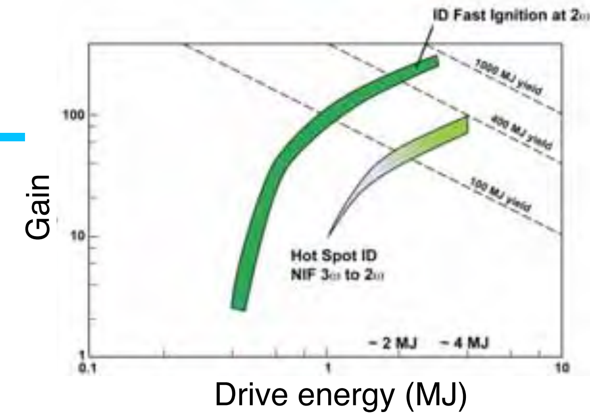
National Nuclear Security Administration

IFE Strategic Planning Workshop
San Ramon, CA
April 25, 2007

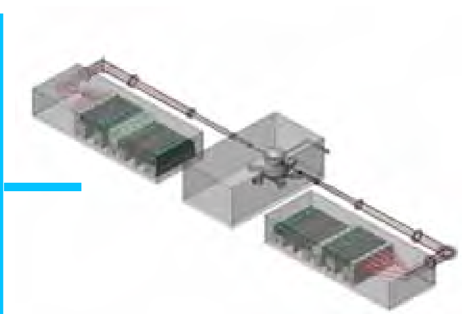
This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

What do we (I) Mean by *Advanced* Targets?

High gain at low drive energy*
→ G≥100 @ E_{drive}≤1MJ



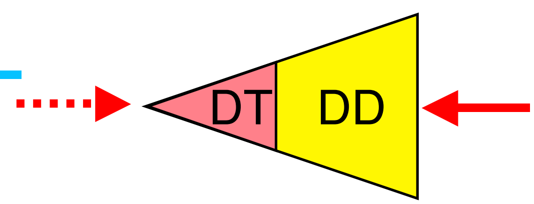
Simple illumination geometries
→ 2(1)-sided drive, thick-liquid walls?

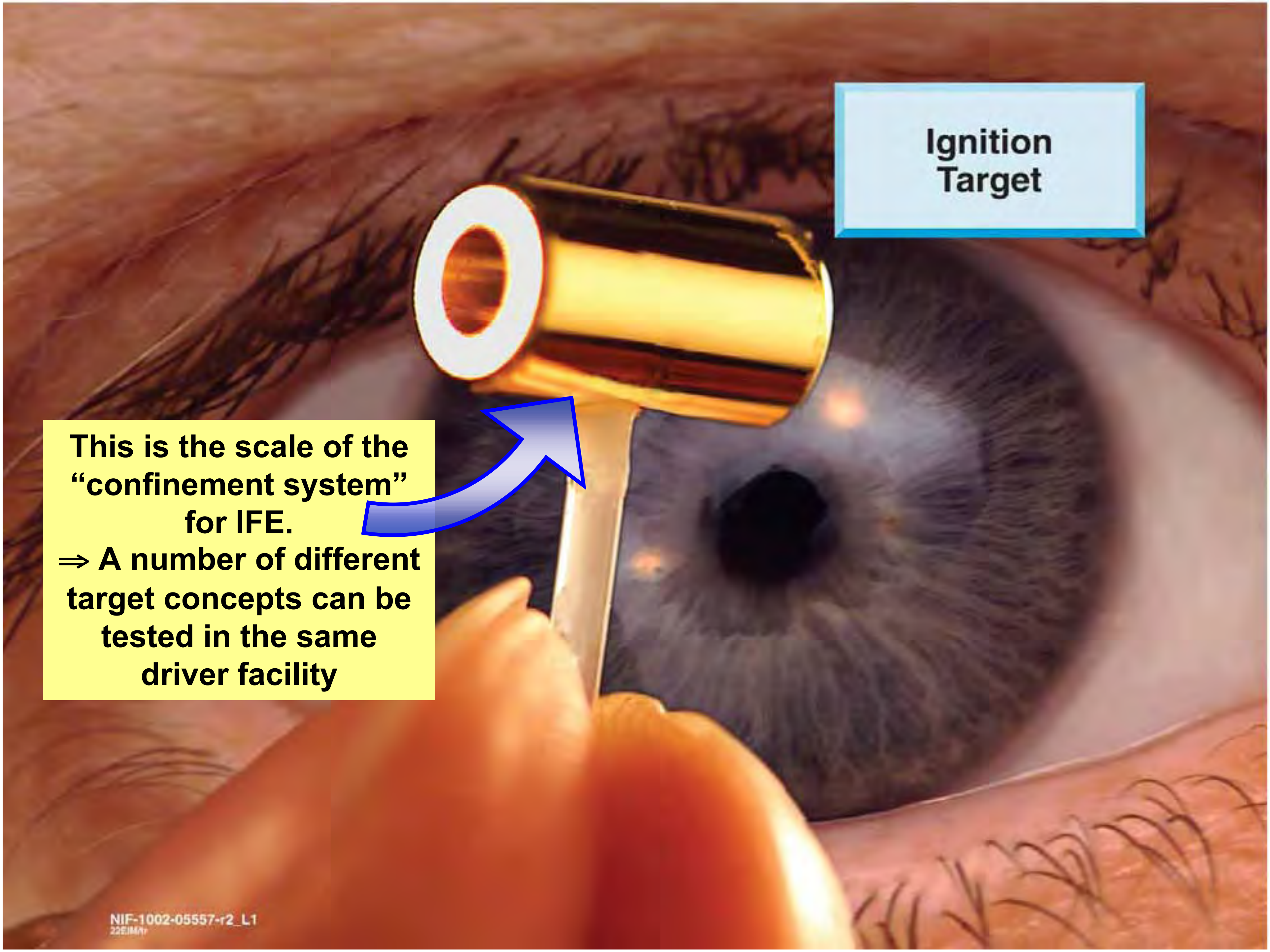


Please, oh please..!

Simple target fab and manufacture
→ Can we avoid cryo?

Can we go beyond D-T?
→ D-D, D-^{3}He, p-^{7}Li, p-^{10}B,…?





Ignition Target
This is the scale of the "confinement system" for IFE.
⇒ A number of different target concepts can be tested in the same driver facility
NIF-1002-05557-r2_L1

Definition of the "Separable" IFE R&D Plan: Roll Back From Where You Need to Go

The IFE R&D program rolls back from this

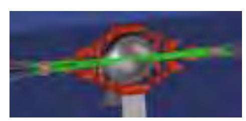
World IFE Program ~2007-2020

- Advanced targets
  NIF, Omega, LMJ, Z…
- Rep-ratable drivers
  ("beamlets")
- Chambers (liquid,solid)
  and nuclear technology
- Support technology
  (target fab, injection, optics…)

High Average Fusion Power Facility ~2015-2025

NRL's FTF

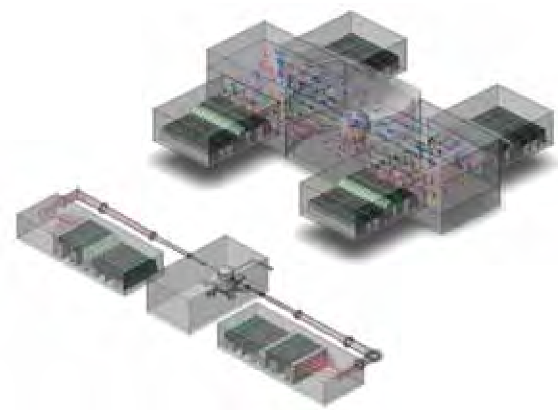
HiPER



HI-FTF, etc…

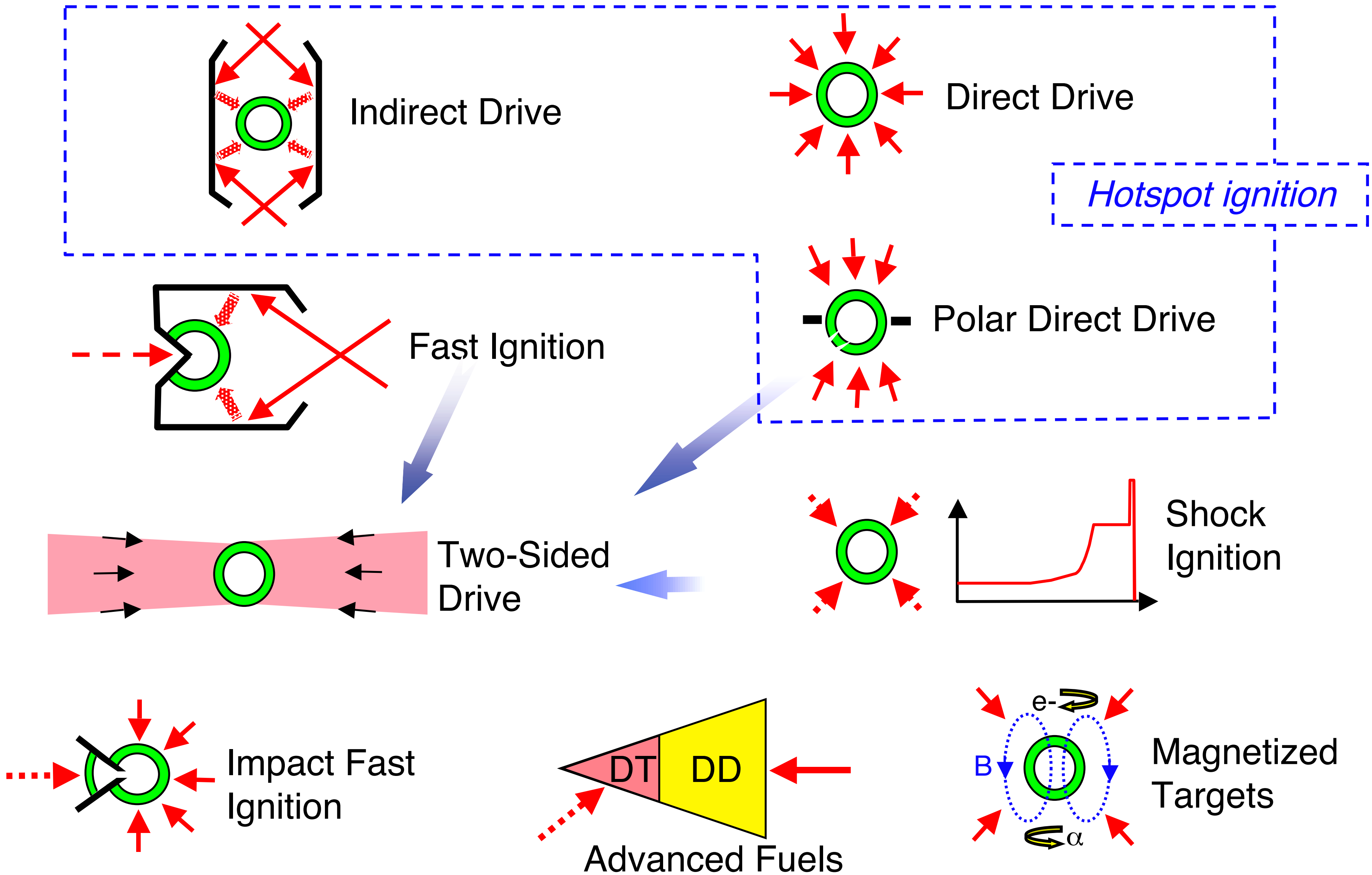
- High av. power 10's-100'sMW
- Demonstrates sustainable fusion energy in steady-state
- Not req'd to demonstrate commercial viability

Attractive Commercial Plant Competitive with Advanced (Breeder) Fission



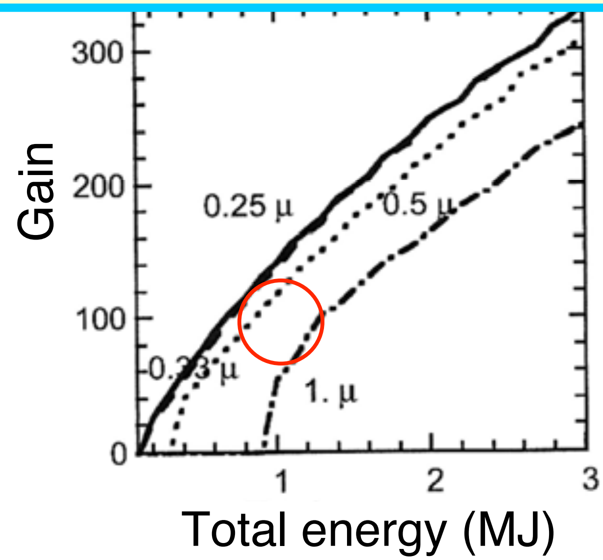
- Electricity (>1GWe)
- Hydrogen production
- Desalinated water
- Fission hybrid (breed/transmute)
- Etc, ….

NIF, Post-Ignition, is the Key Advanced Test Facility for IFE-Relevant Targets at High Gain/Yield (~200MJ)



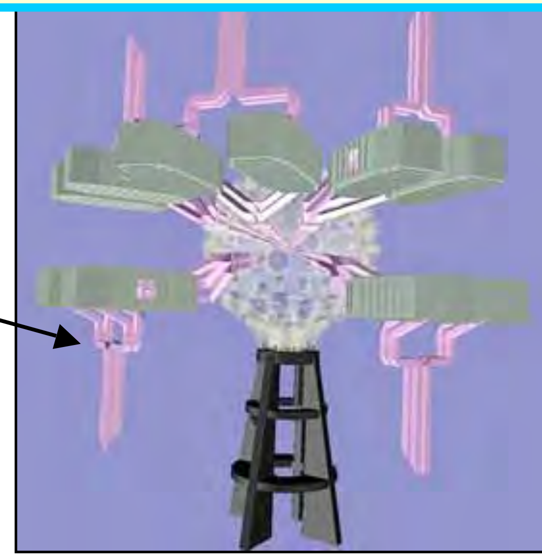
Fast Ignition: Decouple Compression from Ignition (and Alleviate Symmetry/Stability Constraints?)

Gain v. total energy for indirect drive compression at 0.25-1μm.
(Tabak et al, *Fusion Sci.Tech*. 2006)

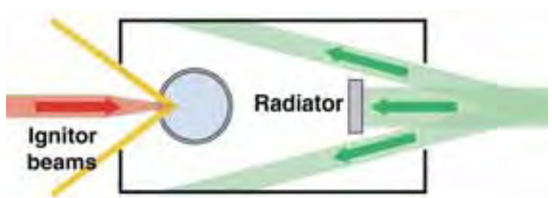


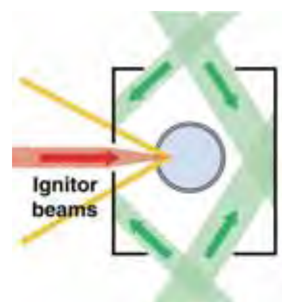
If OMEGA-EP results are promising, NIF could be adapted for ≥60kJ of short pulse energy

5 quads
20 beams
20ps CPA, 1ω
,~60kJ



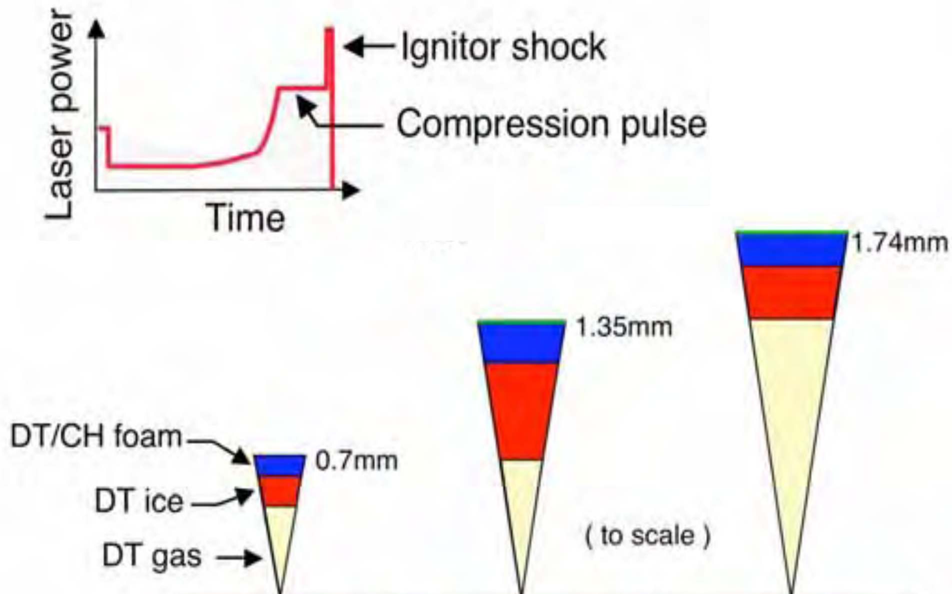
Desired reactor geometry



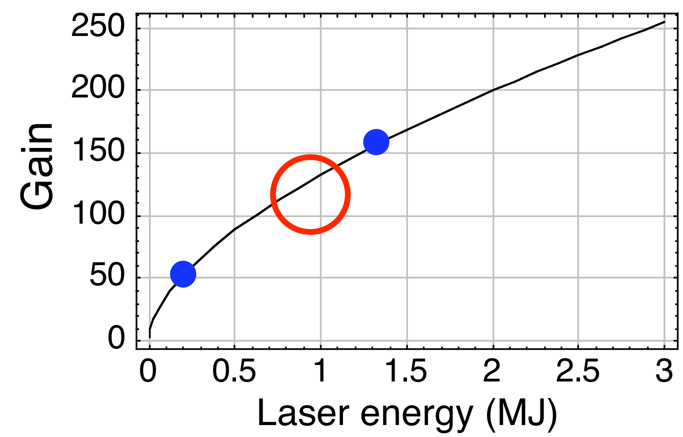


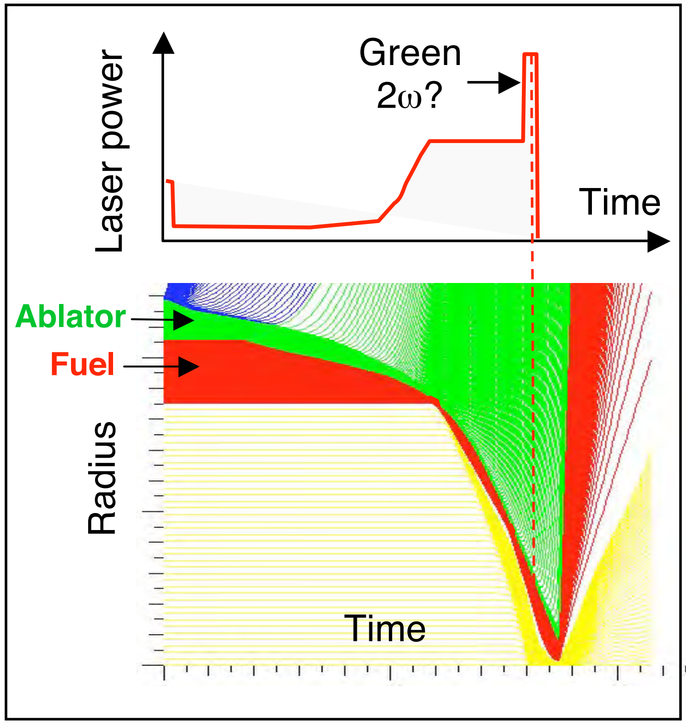
NIF FI geometry

Shock Ignition: Initial LASNEX Results Suggest Promise for Shock-Ignited* Targets on NIF



	Low Energy NIF Target	High Stability NIF Target	High Yield NIF Reactor Target
Laser Energy	160kJ	1MJ	1.3MJ
Gain / Yield	50 / 8MJ	100 / 100MJ	154 / 200MJ
Velocity (cm/s)	2.5e7	1.8e7	2.2e7
Peak intensity(W/cm²)	0.8–4e15	0.9-2.7e15	0.4–1.2e15
IFAR	35	10	33





From a regulatory view, NIF should be able to accommodate yields of ~200MJ

LLNL Site-Wide EIS 2005
- Shot budget = 1200MJ/yr
- 1MJ Indr-drive ign target, nom. yield = 10MJ
- Indr-drive ign target, max cred. yield = 45MJ
- 0.5rem/yr LLNL limit*

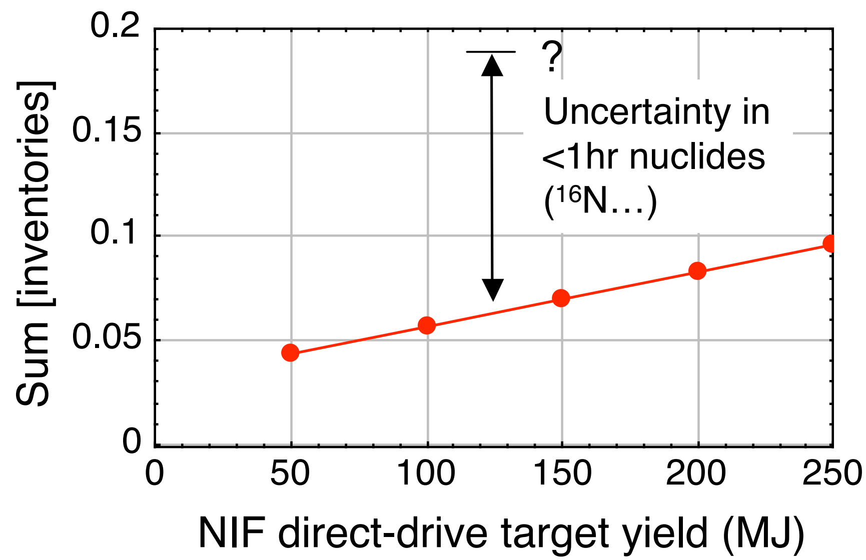
Equivalent NIF Dose Limits
- ~19 person-rems/yr over all personnel**
- 30mrem/yr individual av. (⇒ ~600 people)
- 0.5rem/yr LLNL limit* (⇒ target bay workers)

Changes to EIS to increase yield limits might be just paperwork" until we cross the threshold to a 'Category-3 Nuclear Facility' :

Category	Example
1	Nuclear reactor,Hanford tanks
2	LLNL Pu bldg,
3	LLNL tritium bldg (≤30g T_2)
<3	Radiological facility (e.g NIF)

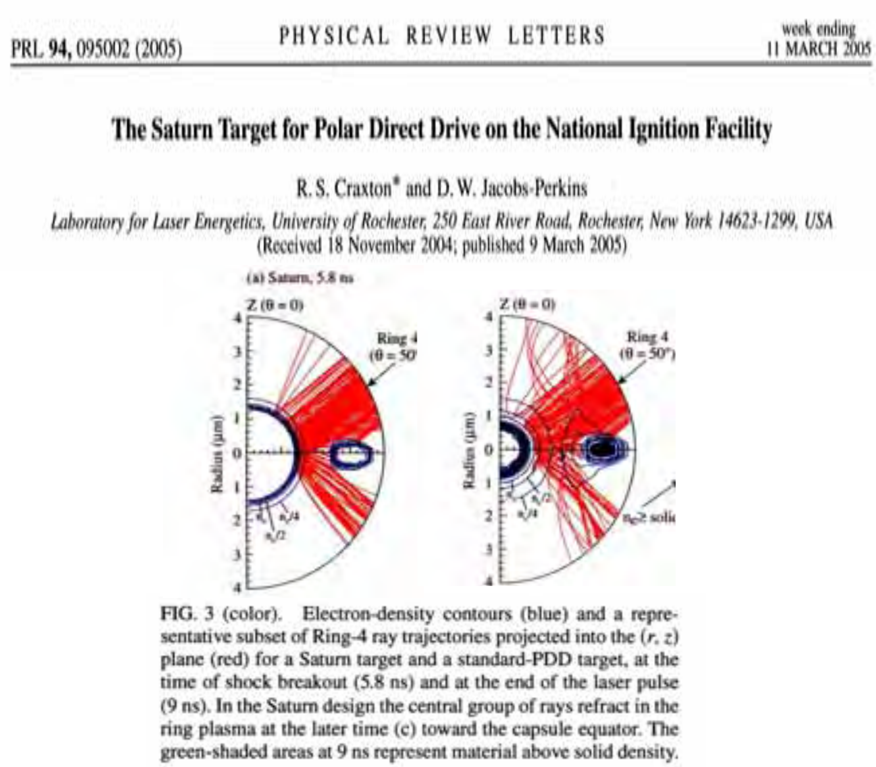
"Less than Category-3" Facility requires:

Sum **[**partial *releasable* inventories**]** < 1.0
(⇒ <10rem@30m)



*NRC worker limit = 5rem/yr; DOE limit = 1rem/yr

LLE/Rochester's NIF Polar-Direct-Drive ("Saturn") Target: Gain~17 with all 2D Sources Applied


PRL 94, 095002 (2005) PHYSICAL REVIEW LETTERS week ending 11 MARCH 2005

The Saturn Target for Polar Direct Drive on the National Ignition Facility

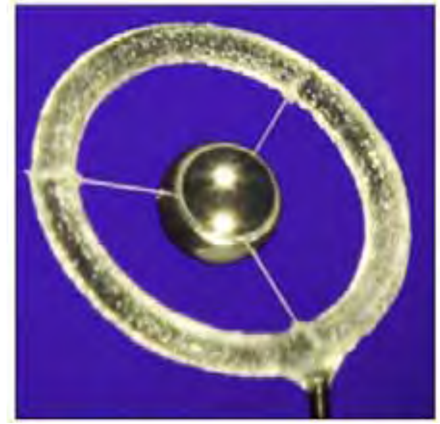
R. S. Craxton* and D. W. Jacobs-Perkins

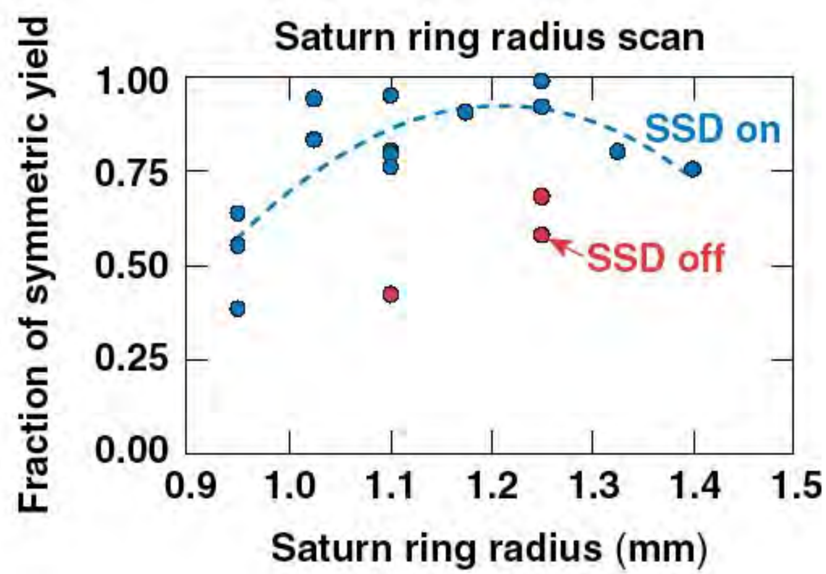
Laboratory for Laser Energetics, University of Rochester, 250 East River Road, Rochester, New York 14623-1299, USA

(Received 18 November 2004; published 9 March 2005)

FIG. 3 (color). Electron-density contours (blue) and a representative subset of Ring-4 ray trajectories projected into the (r, z) plane (red) for a Saturn target and a standard-PDD target, at the time of shock breakout (5.8 ns) and at the end of the laser pulse (9 ns). In the Saturn design the central group of rays refract in the ring plasma at the later time (c) toward the capsule equator. The green-shaded areas at 9 ns represent material above solid density.

"Saturn" polar direct drive targets have been shot on Omega and have achieved ~80-90% of the full 4-Pi symmetric yield

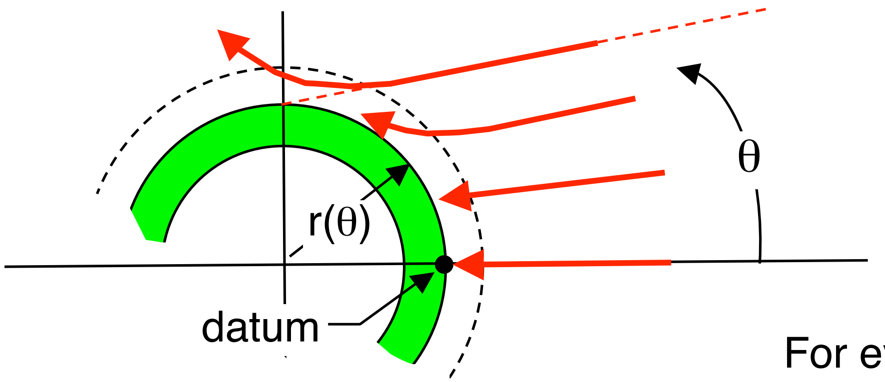


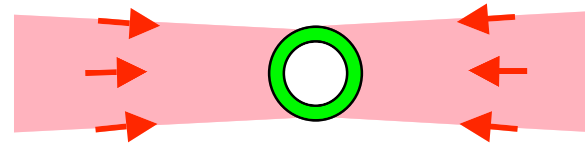


F.Marshall, *Bull APS* **51** 106 (2006)

⇒How small an illumination angle can we achieve?
(±25% max, ≤±10% desired)

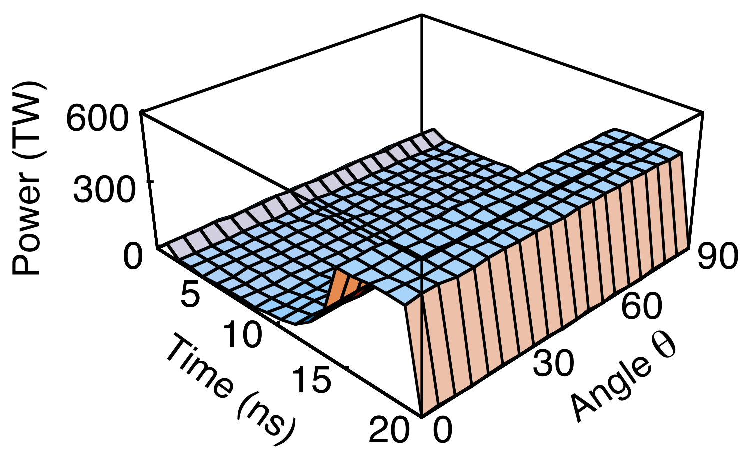
We Have Established a Methodology for Modeling Two-Sided Laser Direct Drive in LASNEX



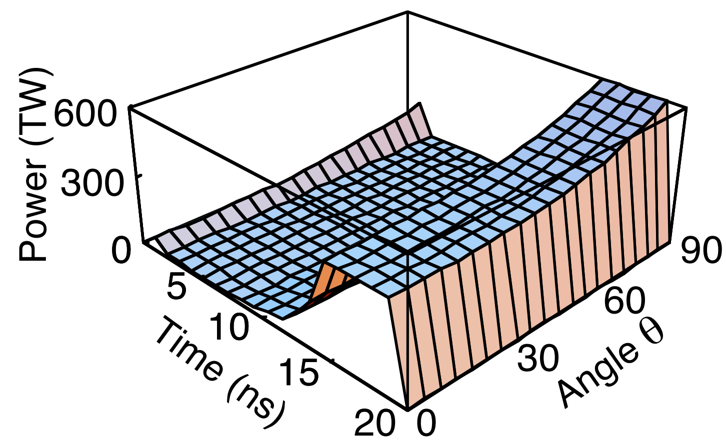


For every LASNEX time step, adjust power on each ray as:

$$I(\theta) \sim \frac{I(0)}{\cos(\theta)} \left(\frac{r(\theta)}{r(0)} \right)^{3/2} f_{Map}(\theta)$$



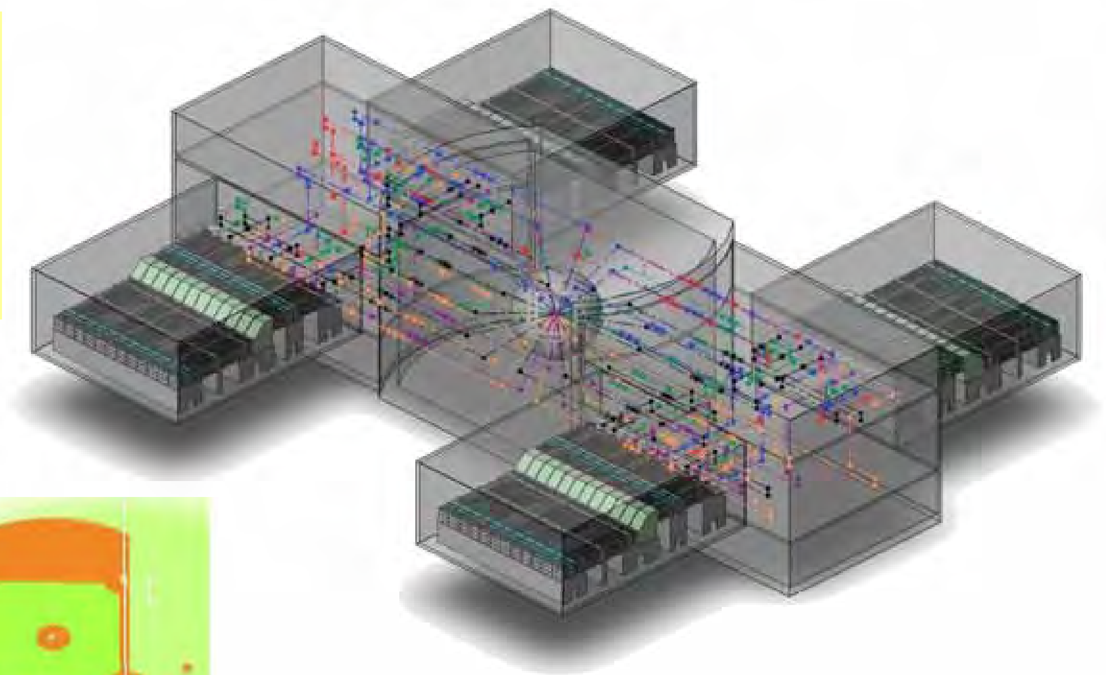
Laser Pulse Shape – Symmetric 4Pi Illumination

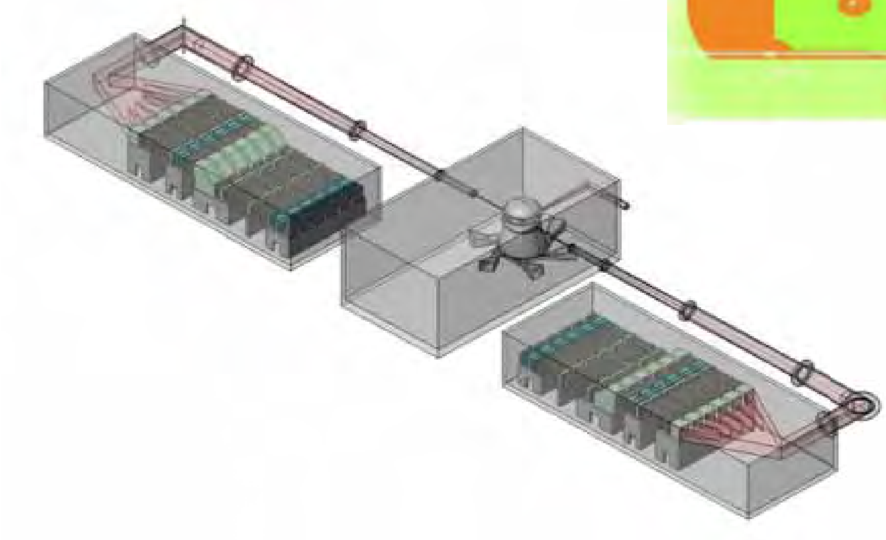


Laser Pulse Shape – Two-sided Illumination

Advanced Targets are Central to Attractive Commercial Fusion Reactors

Conventional Direct Drive
- 4Pi illumination
- Gain ~125-150@2.5-3MJ
- Drywall chamber
- DPSSLs at 3ω





2-Sided Direct Drive + Shock/Fast Ignition
- 2-sided illumination
- Gain ~200@1MJ
- Liquid wall chamber

G.Logan (LBNL/HIF-VNL) is Revisiting T_2-Lean D-D Targets in the Context of Heavy-Ion Direct Drive

T-lean fuel assemblies for MHD direct conversion Develop and benchmark MCAD model based on Tabak's Case C run[1] for isobaric hot spot ignition (see Fig. 1) with his f = 0.1 tritium parameter (to maximize non-neutron yield for direct conversion with ηG_f>100 for low recirculating power)

TABAK

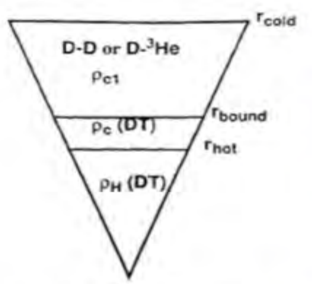


FIG. 1. Pie diagram of compressed core.

[1] Max Tabak, Nuc. Fusion 36, No2 (1996). Calculates DD burn assuming 10 keV initial DT hot spot. (If needed, a late shock (Betti- Perkins) could be applied to insure ignition at lower implosion velocities and at lower adiabats, say α=1.5 instead of at α=2 as Max assumed). We assume DD main fuel instead of D-^{3}He for reasons Max stated.

Fuel assembly energy (variable) (MJ) $ORIGIN := 1$

Min tritium loading parameter for ηG>100

For $i := 1..7$ $\quad Ef_i := 0.05 + 0.05 \cdot i^2$ fuel energy cases

$f := 0.1$ $\quad r_{bound}(r_{hot}) := r_{hot} \cdot (1 + 2 \cdot f)$ DT radius

$\zeta := 1 - (1 + 2 \cdot f)^{-3}$ DT load parameter

Use Max's formulary[1] for fuel assemblies optimizing gain for given fuel energies:

The Heavy Ion Fusion Virtual National Laboratory PPPL

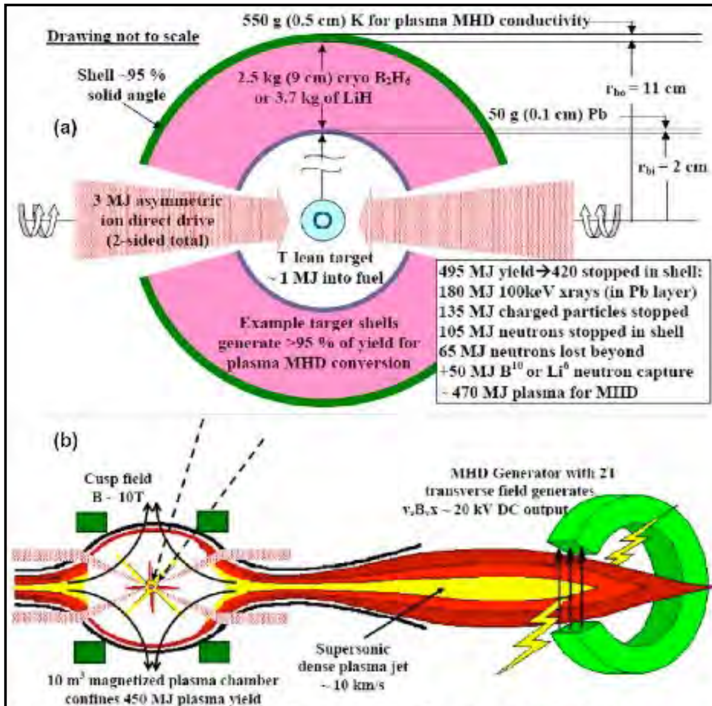
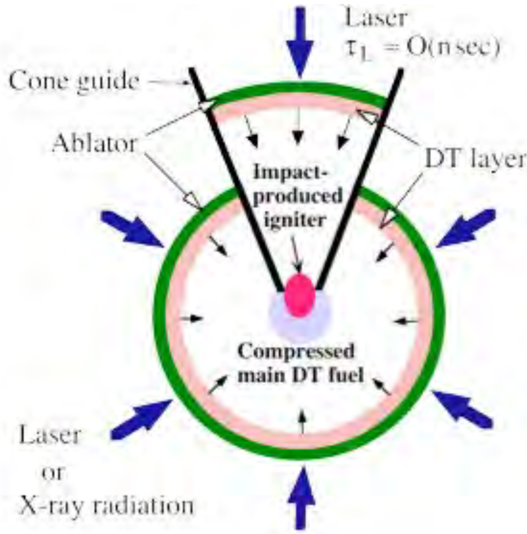
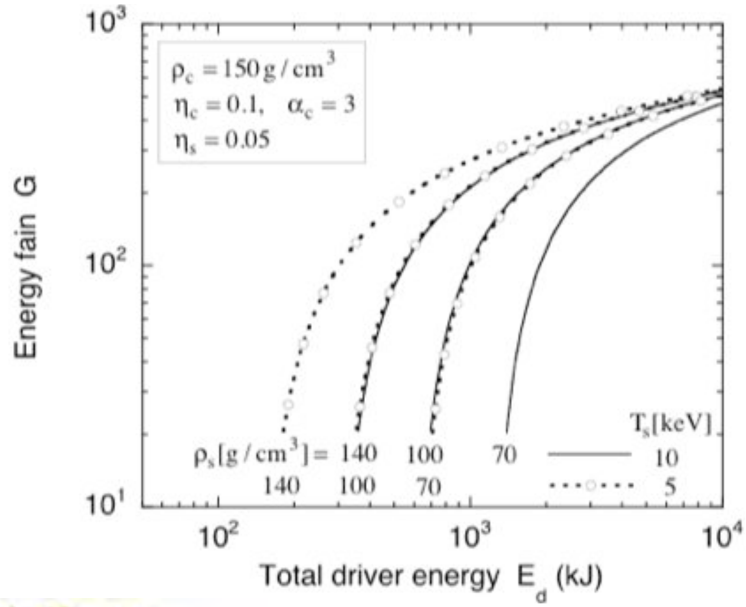


Figure 4: (a) Example target shell for efficient conversion of T-lean target output into 1 to 2 eV dense plasma for direct MHD conversion. All shell materials condense and recycle (Rankine cycle). (b) Schematic of the CFAR MHD scheme (adapting the old 1992 CFAR Logo!)--no detailed design yet.

- Heavy ion direct drive for potential 4X coupling efficiency and target gain
- Fast ignition or shock ignition to enhance gain
- T_2-lean DD targets with reasonable size drivers (<3MJ)
- Efficient capture (>90%) of fusion yield for plasma direct conversion

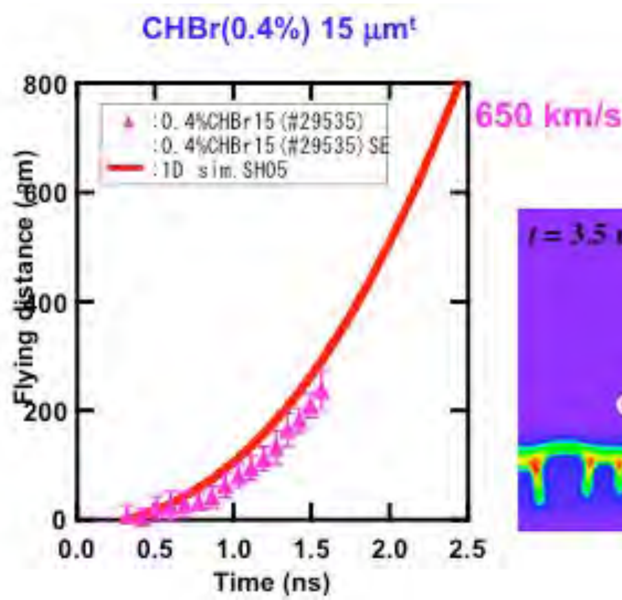
Impact Fast Ignition (M.Murakami - ILE Osaka)

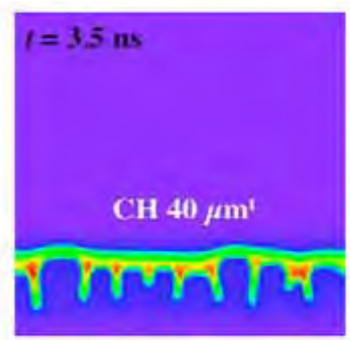


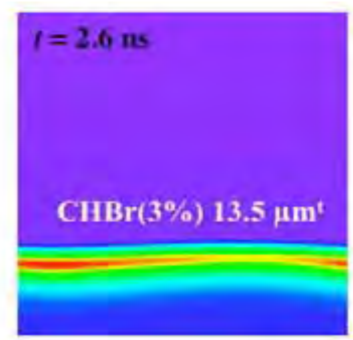


Very high velocities (~10^8cm/s=1000mk/s) will be required with reasonable R-T growth.

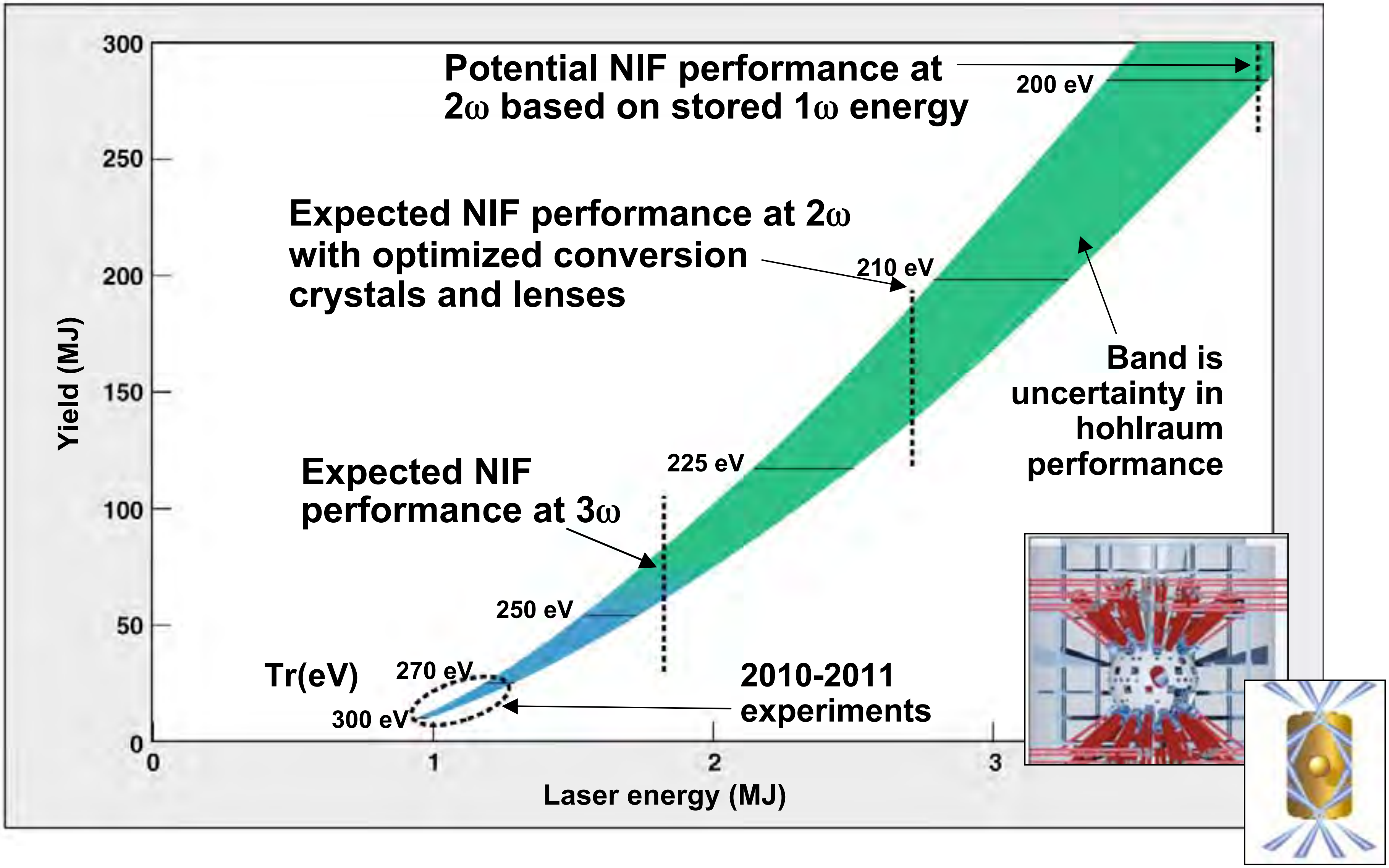
650km/s has been obtained experimentally.







High Yield NIF Targets may be Achievable with Conventional Indirect Drive



J.Lindl “Ignition Campaign Strategy” 2007

Definition of the "Separable" IFE R&D Plan: Roll Back From Where You Need to Go

The IFE R&D program rolls back from this

World IFE Program ~2007-2020

Advanced targets
NIF, Omega, LMJ, Z…

Rep-ratable drivers ("beamlets")

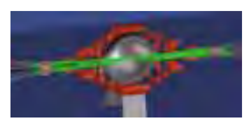
Chambers (liquid,solid) and nuclear technology

Support technology (target fab, injection, optics…)

High Average Fusion Power Facility ~2015-2025

NRL's FTF

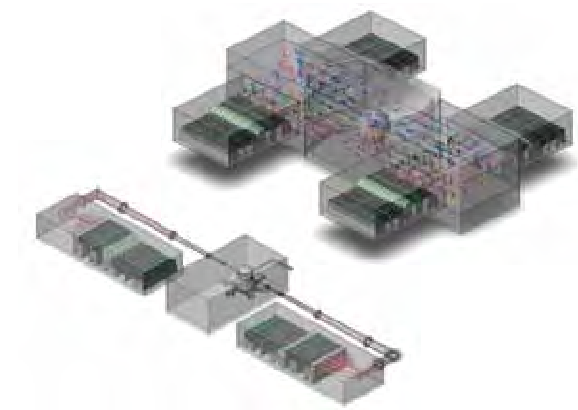
HiPER



HI-FTF, etc…

- High av. power 10's-100'sMW
- Demonstrates sustainable fusion energy in steady-state
- Not req'd to demonstrate commercial viability

Attractive Commercial Plant Competitive with Advanced (Breeder) Fission



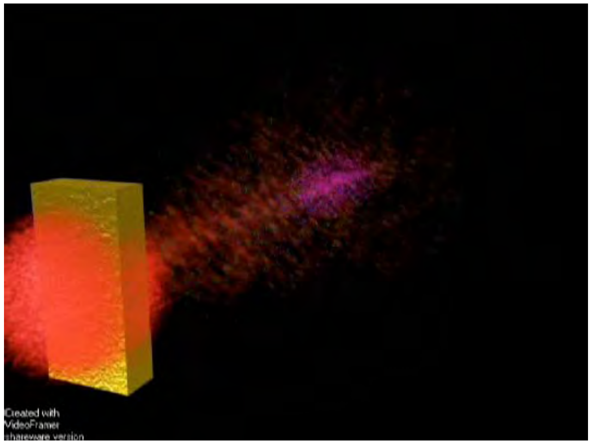
- Electricity (>1GWe)
- Hydrogen production
- Desalinated water
- Fission hybrid (breed/transmute)
- Etc, ….

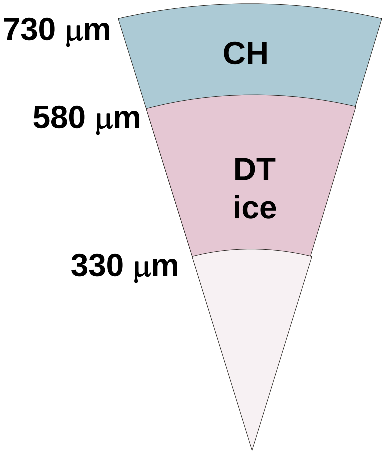
Ion-Driven Fast Ignition: Scientific Challenges and Tradeoffs*

LA-UR-07-2686

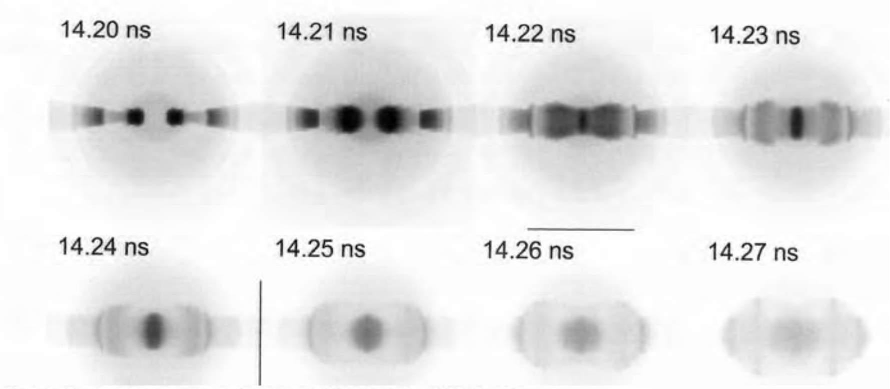
presented by:
Juan C. Fernández
Los Alamos National Laboratory

presented to:
IFE Science & Technology
Workshop
San Ramon, CA
April 24-27, 2007





Capsule x-ray self emission (14.2 keV - 106 keV)



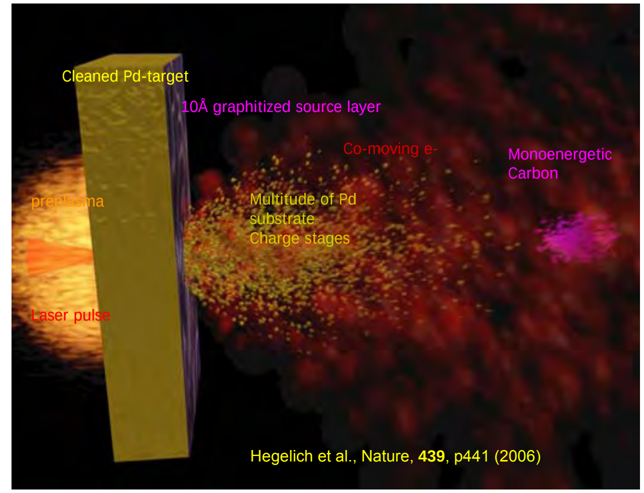
Capsule x-ray self emission (14.2 keV - 106 keV)

Collaborators, contributors, acknowledgements:

- LANL
  - B. Albright, M. J. Schmitt, Lin Yin (X-1, Applied Physics)
  - K. Flippo, B. M. Hegelich (P-24 Plasma Physics)
- LLNL
  - Photon Science & Applications Group
- Acknowledgements
  - LANL LDRD Program Office
  - OFES

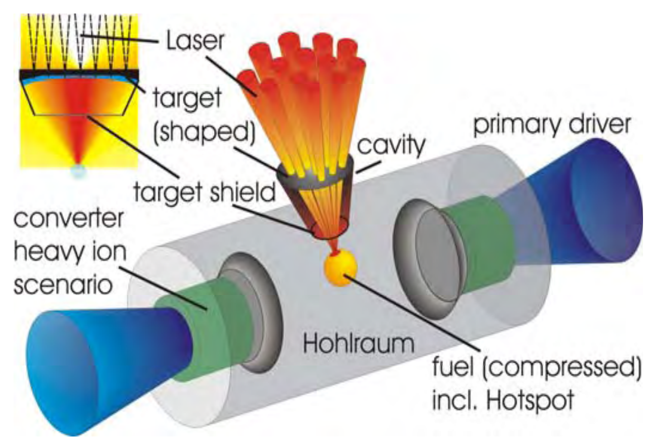
Outline:

- Summary of fast ignition (FI) requirements, issues & challenges



- Potential advantages of alternate concepts
  - *E.g.,* C-ion based FI

- Integrated calculation of C-based FI

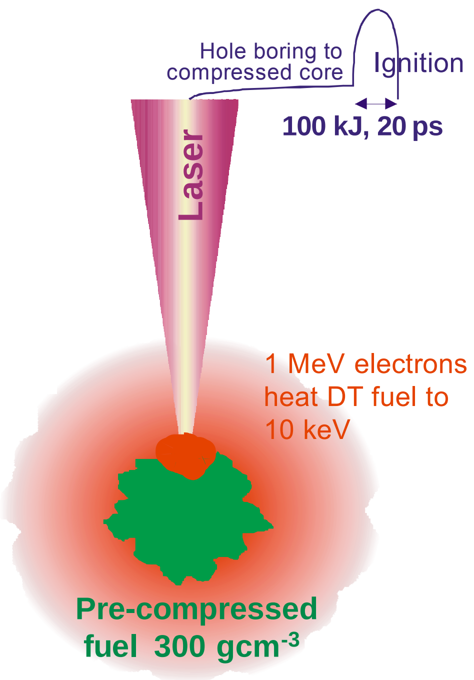


- Comparison of challenges and advantages of different concepts

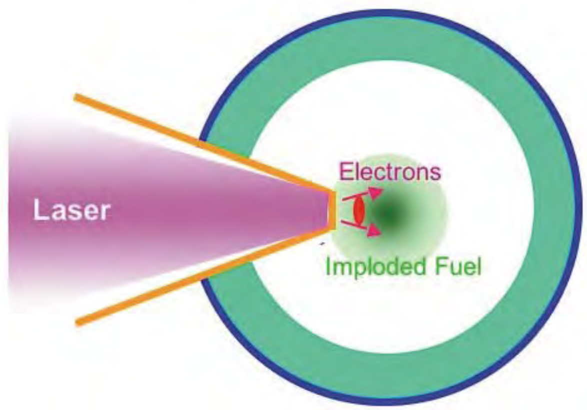
- Summary

Summary of fast ignition requirements:

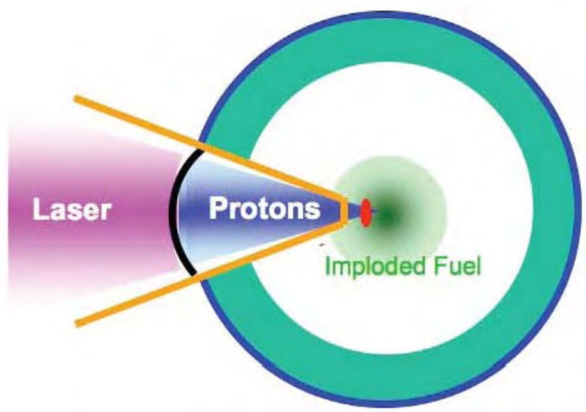
- Fast ignition (FI) requirements:
  - Long-pulse (> 10 ns) driver to compress DT to 300 – 500 g/cm^3
  - Particle beam to deposit a minimum of ~ 10 kJ within hot-spot (HS) volume (~ 25 μm)^3 in ~ 20 ps.



M. Tabak *et al*., PoP **1** 1626 (1994)



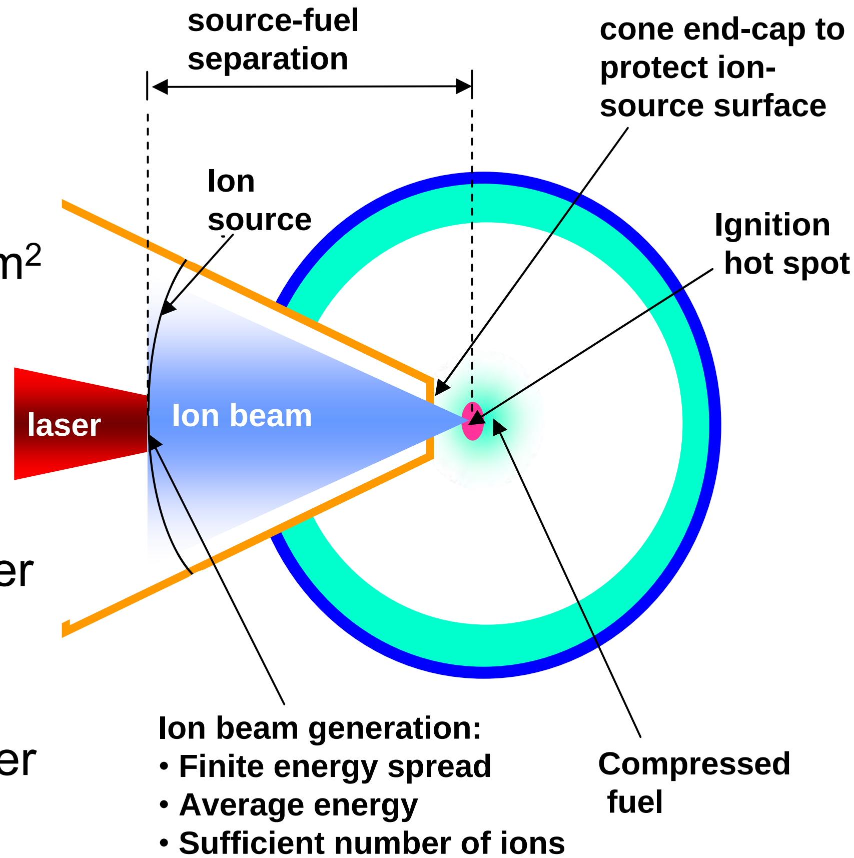
R. Kodama *et al*., Nature **412** 798 (2001)



M. Roth *et al*., PRL **86** 436 (2000)

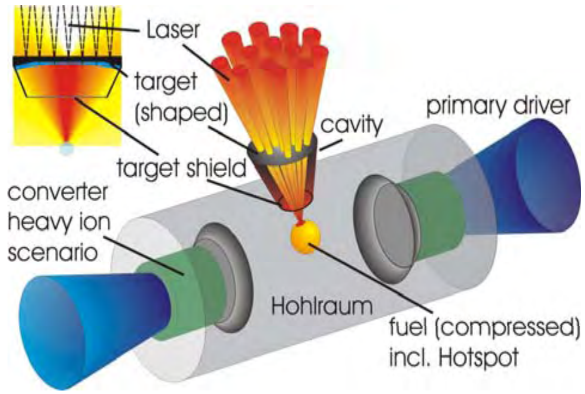
General issues relating to fast ignition:

- Fuel assembly
  - Beam-source target shielding from implosion
- Laser conversion efficiency to particle beam
  - Laser → hot e^- or e^- ignitor beam
  - Hot e^- → ion ignitor beam
- Hot spot ρr ~ particle range → laser I
  - e^- → ~ 1 MeV → $I \sim 5\times10^{19}$ W/cm²
  - Protons → ~ 13 MeV → $I \sim 10^{20}$ W/cm²
  - C → 440 MeV → $I \sim 10^{21}$ W/cm²
- Power & I → target area (TA)
  - Consistency problem for e^- (TA >> HS area)
- Total & particle energies → particle number
  - Thick proton target layers
- Particle beam energy spread
  - Low spread → thin target surface layer
- Particle-beam transport
  - Focusing / instabilities
  - Arrival time spread (energy spread + source-fuel separation)



C-based

Quasi-monoenergetic C ions have potential advantages as a fusion ignitor beam.



- Fast ignition (FI) Requirements:
  - Long-pulse (> 10 ns) driver to compress DT to 300 – 500 g/cm^3
  - Particle beam to deposit ~ 10 kJ within (~ 25 μm)^3 in ~ 20 ps.
- Potential advantages over electron* or proton-based[1] FI:
  - Beam source separate from the fuel (more control)
  - Ion range in the fuel better matched than electrons (efficiency)
  - More robust beam transport than with electrons (more stable)
  - Requires fewer ions than protons (easier target Fab.) & smaller current (more stable)

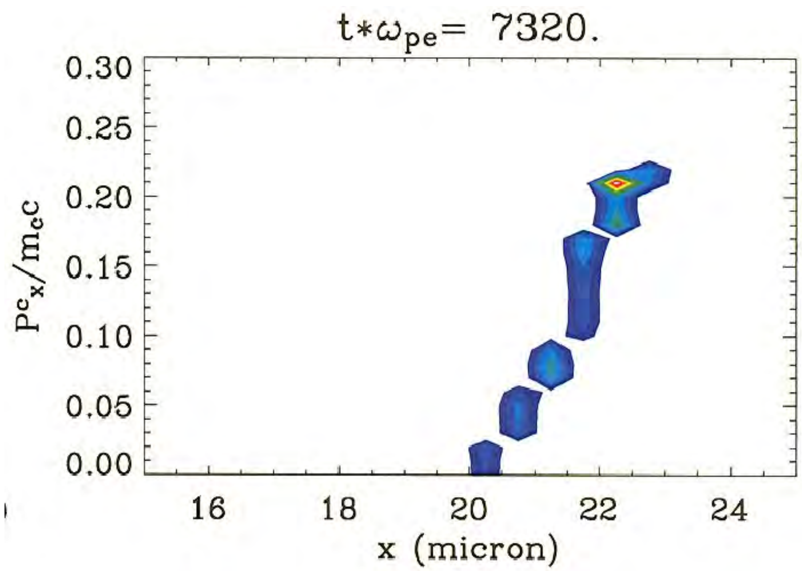
Beam Ion	Energy (MeV)	Number of Ions	Laser Irrad. (W/cm^2)	Minimum areal densities, layer thickness @ 1 mm^2
Protons	7 – 19	10^{16}	~ 10^{20}	10^{18} cm^{-2}, ~ 200 nm (CH)
C^{6+}	400-480	10^{14}	~ 10^{21}	10^{16} cm^{-2} , ~ 1 nm

* Tabak *et al*., PoP **1**(1994) 1626

[1] Roth *et al*., PRL **86** (2001) 436

C-based

The laser-breakout afterburner*: a path to high efficiency & high energy ion beam.



- Requirements:
  - $I \sim 10^{21}$ W/cm^2 with ultra-high laser contrast
  - Ultra-thin targets (*e.g.*, ~ 30 nm C)
- 1D & 2D Simulations using VPIC code
  - Start with solid density C, including cases with H contaminants
- Mechanism:
  - Laser penetration across target
  - Electron heating
  - Electron energy $\rightarrow$ ion energy via kinetic Buneman instability.
- Initial Results:
  - 35% (1D, 15% in 2D) of all ions accelerated to 0.3 GeV $\pm$ 7%, 4% conversion efficiency.
  - C-ion acceleration is immune to surface proton contamination!

This concept is the new focus of LANL research in ion-beam generation

* Yin *et al.*, Laser and Part. Beams **24,** P. 291 (2006); Phys. Plasmas **14,** 056706 (2007)

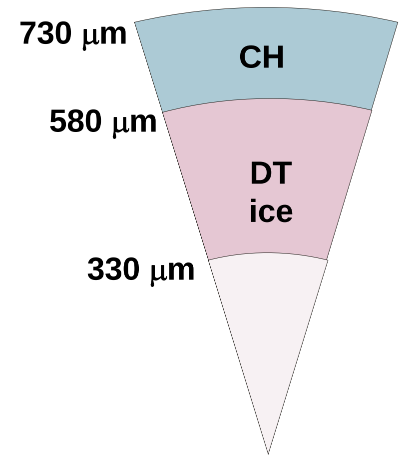
Multiple FI approaches should be pursued: they all have advantages & challenges

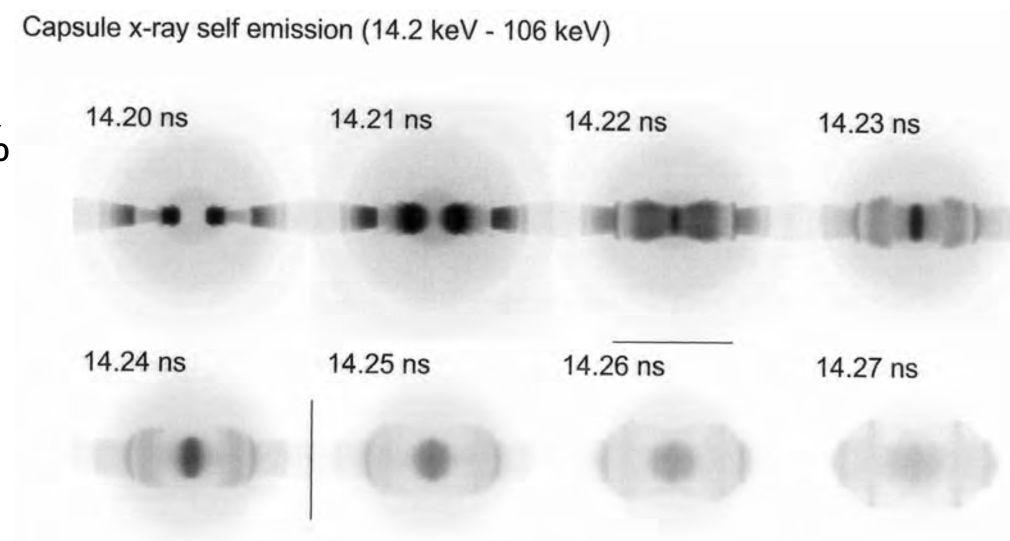
Difficulty index:
Easy, Moderate, Challenge
TA, HAS: target, hot-spot area

Beam Particle / Issue	Electrons	Protons (Maxwellian, cone target)	Carbon (quasi-mono-energetic)
Implosion / target Fab.	Easy (hole boring) Challenge (cone)	Challenge (cone)	Easy (no cone, long standoff)
Shielding beam-generating target from implosion	Not applicable (hole boring) Moderate (cone)	Challenge (short standoff)	Easy (long standoff)
Laser beam propagation to beam-generating target	Challenge (hole boring) Moderate (cone)	Moderate (cone)	Easy (long standoff)
Particle energy	Easy	Easy	Challenge
Laser requirements	Easy	Moderate	Challenge (Hi Contr.)
High laser conversion Eff.	Easy	Moderate (modeling)	Challenge (optimize)
Particle-beam transport, focusability	Not applicable (hole boring) Challenging (cone)	Easy (stiff beam)	Easy (stiffest beam)
Consistency, TA versus HSA	Challenging (TA >> HSA)	Easy	Easy
Required # of particles	Easy	Moderate (thick layer)	Easy (thin layer)
Arrival-time spread / standoff	Easy	Challenging (short standoff required)	Easy
Minimize HS volume	Challenging (range, Instab.)	Moderate	**Easy (Bragg peak)**

Illustrative integrated LASNEX simulation in 2D shows advantages of a C ignitor beam in minimizing hot-spot volume.

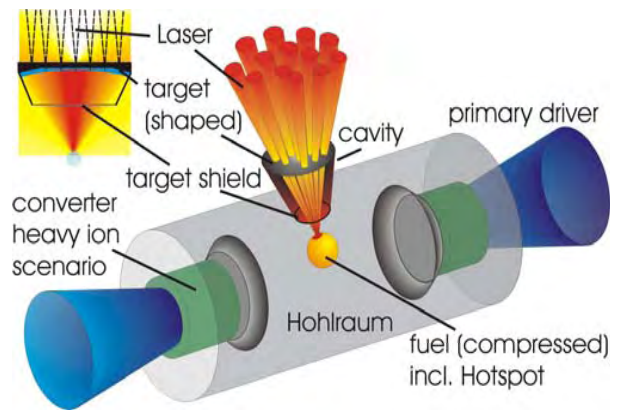
- Simulated experiment (~ 2 FTE-week effort):
  - Capsule compression with radiation source
  - C ignitor beam
- Capsule implosion
  - Compression with radiation source
  - 14.2 ns pulse (foot + $P \sim t^{3.5}$ pulse)
  - Energy absorbed: 35.5 kJ
  - Fuel density: ρ_{DT} ~ 150 g/cc
- Two (symmetric) C ignitor beams
  - Ion energy: 375 MeV ± 37.5%
  - Beam energy: 7.2 kJ Ea.
- Results:
  - Two ignition spots,
    15μm diameter, 10μm long
  - Fusion Gain in 2D = 2,
    i.e. 2 × (35.5 + 14.4) kJ

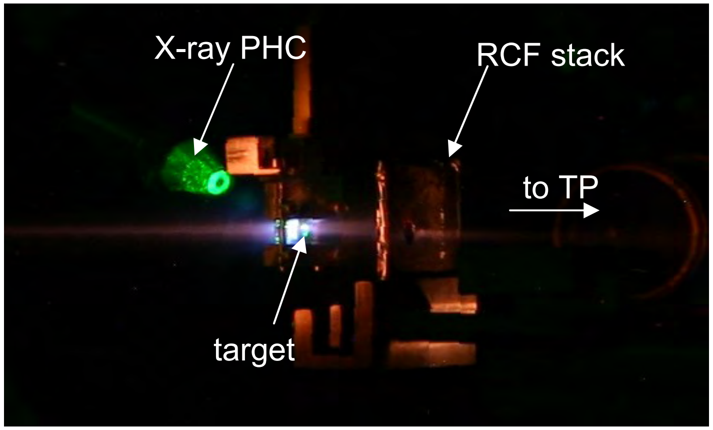




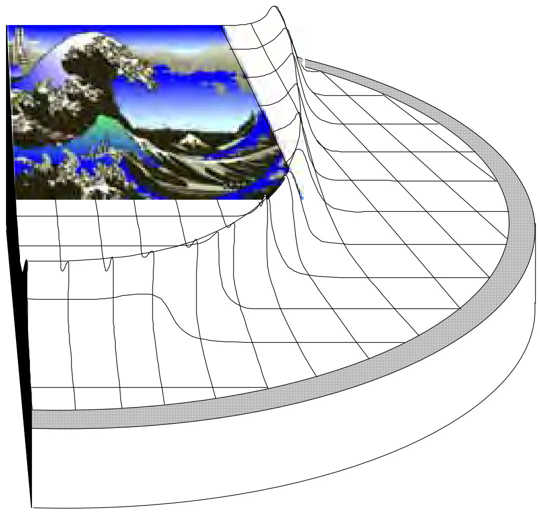
Summary:

- The general requirements for FI have been summarized.
- The FI issues, challenges and difficulties have been discussed.
- A novel FI concept based on a laser-driven C-ignitor beam has been presented
- An integrated simulation of a FI experiment to test the concept has been presented.
- The advantages and challenges of electron-based, proton-based and C-based FI have been summarized.
- Conclusion: it is too early to downselect - alternative concepts should be explored.





Thick Liquid Protection of IFE Chambers



Per F. Peterson

Department of Nuclear Engineering
University of California, Berkeley

Inaugural IFE Science and Technology Strategic Planning Workshop: Updates on Progress, Visions, and Near-Term Opportunities

April 26, 2007

Outline: Thick liquids can replace fusion materials questions with fluid mechanics questions

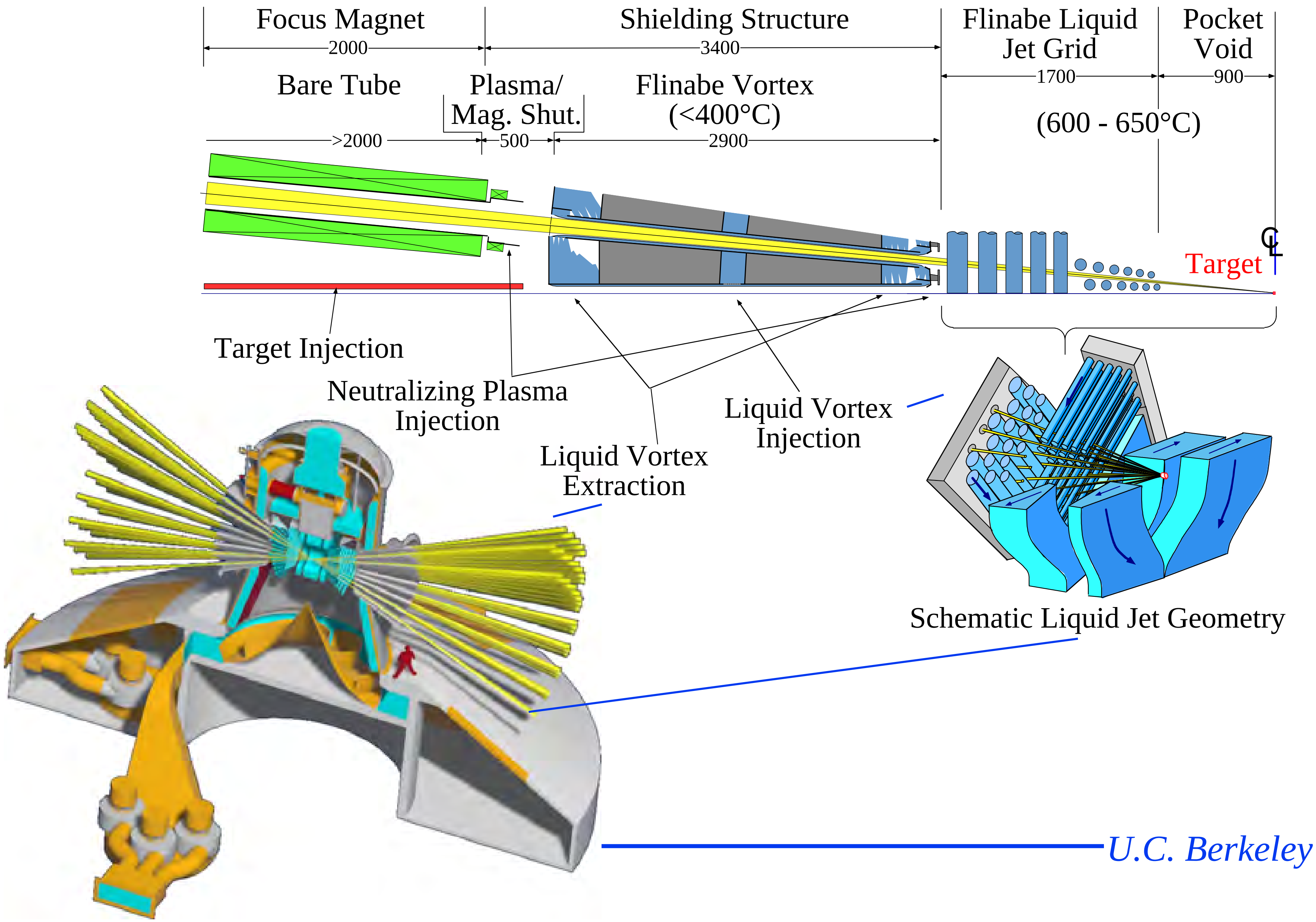
- The scaling basis for understanding and predicting thick-liquid IFE chamber performance
- Past progress
  - RPD 2002
  - Chamber gas dynamics
  - Molten salt vapor pressure
    - Liquid disruptions
- Vortex flows and vortex chambers
- Related progress in fission energy

IFE system phenomena cluster into distinct time scales

Principal focus for IFE Technology R&D...

- **Nanosecond IFE Phenomena**
  - Driver energy deposition and capsule drive (~30 ns)
  - Target x-ray/debris/neutron emission/deposition (~100 ns)
- **Microsecond IFE Phenomena**
  - X-ray ablation and impulse loading (~1 μs)
  - Debris venting and impulse loading (~100 μs)
  - Isochoric-heating pressure relaxation in liquid (~30 μs)
- **Millisecond IFE Phenomena**
  - Liquid shock propagation and momentum redistribution (~50 ms)
  - Pocket regeneration and droplet clearing (~100 ms)
  - Debris condensation on droplet sprays (~100 ms)
- **Quasi-steady IFE Phenomena**
  - Structure response to startup heating (~1 to 10^4 s)
  - Chemistry-tritium control/target fabrication/safety (10^3-10^9 s)
  - Corrosion/erosion of chamber structures (10^8 sec)

The HIF Robust Point Design provided the first demonstration of an integrated HIF chamber design



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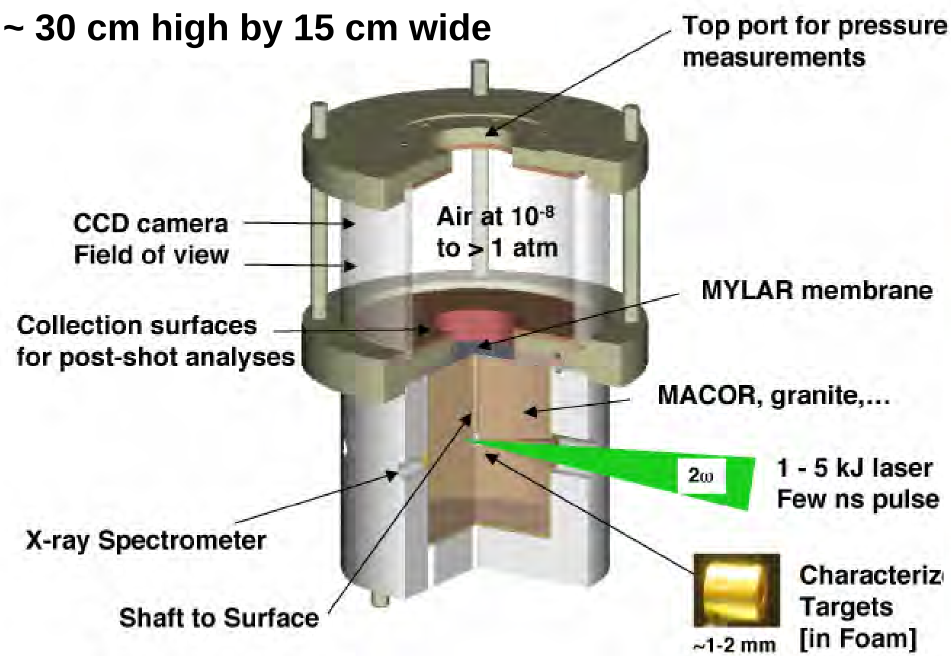
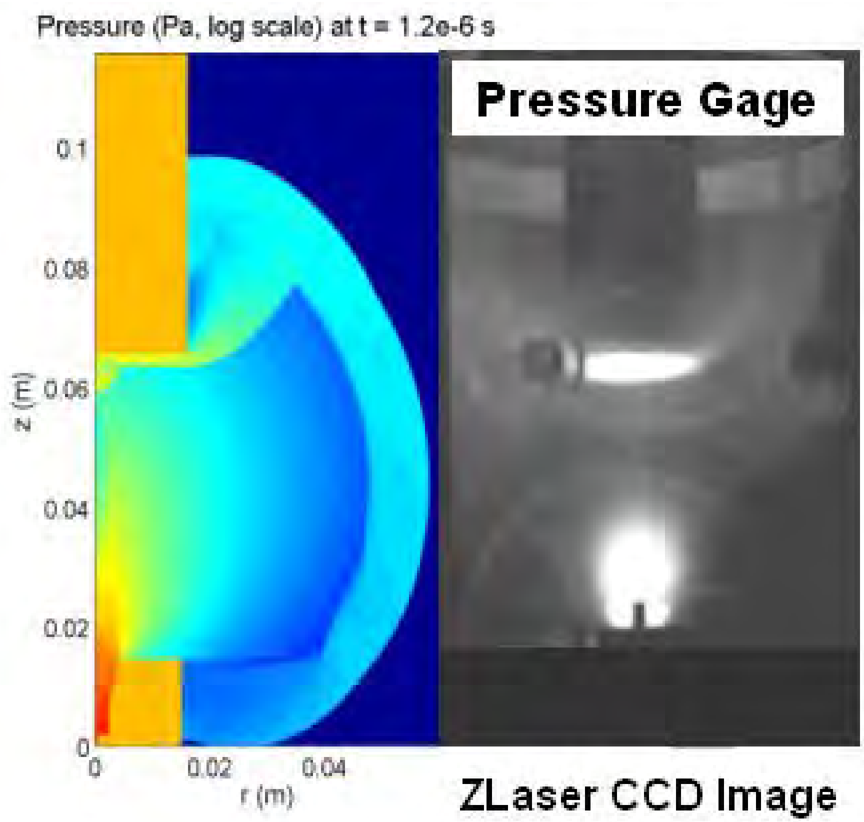
Validation of the gas dynamics code TSUNAMI through LLNL's Condensation Debris Experiment

~ 30 cm high by 15 cm wide



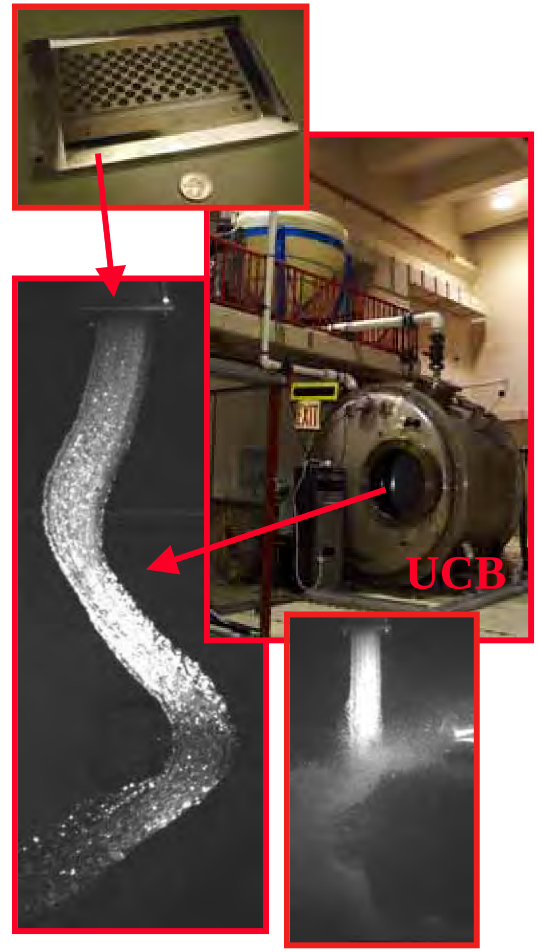


Experimental and numerical results are in good qualitative and quantitative agreement

Scaled water experiments are demonstrating the capability to form the jets used in RPD-2002

High-Re Cylindrical Jets

Vortex Layers for Beam Tubes

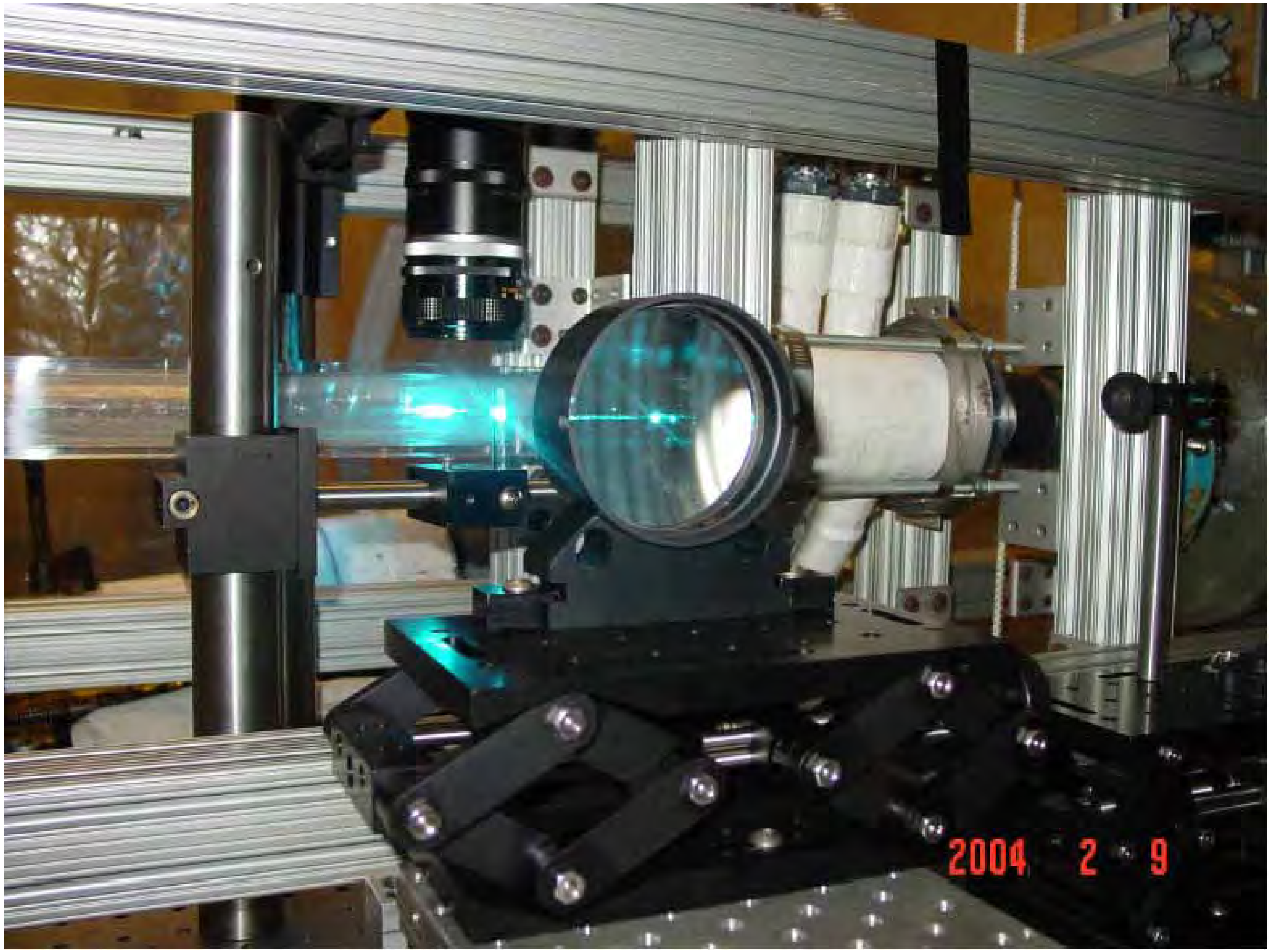


Oscillating Voided Liquid Slabs

Penreco® Drakesol® 260 AT light mineral oil allows molten salt scaled experiments with low distortion

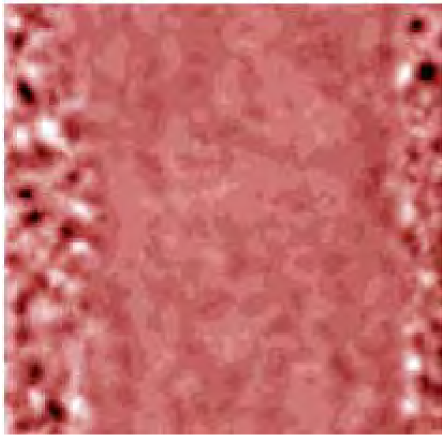
			Flibe at 600°C	Flibe at 900°C
Adjustable Parameters	Oil Temperature		110°C	165°C
	Length-Scale	L_s/L_p	0.40	0.39
	Velocity-Scale	U_s/U_p	0.63	0.62
	Δ T-Scale	$\Delta T_s/\Delta T_p$	0.36	0.40
Reynolds Number		Re_s/Re_p	1	1
Froude Number		Fr_s/Fr_p	1	1
Weber Number		We_s/We_p	0.63	0.72
Prandtl Number		Pr_s/Pr_p	1	1
Rayleigh Number		Ra_s/Ra_p	1	1
β ΔT		$\beta\Delta T_s/\beta\Delta T_p$	1	1
Nusselt Number		Nu_s/Nu_p	1	1
Pumping Power		Qp_s/Qp_p	0.015	0.015
Heating Power		Qh_s/Qh_p	0.012	0.013

UCB performed detailed experimental measurements of turbulence and surface topology in vortex tubes

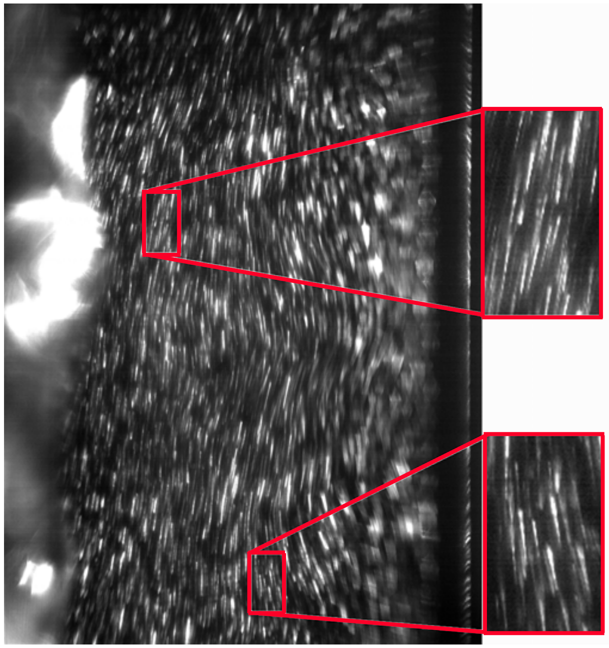


Particle image velocimetry is providing detailed velocity and turbulence information

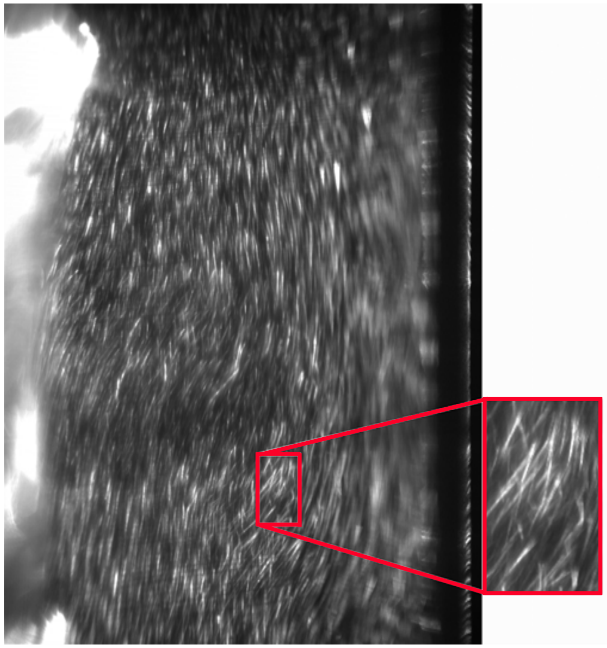
- **Ar CW laser allows visualization of micron particles**
- **Water has been replaced by Mineral Oil for improved visualization**
- **Evidence for intense turbulence at small length scales**



Layer vorticity structure



200 μs exposure time



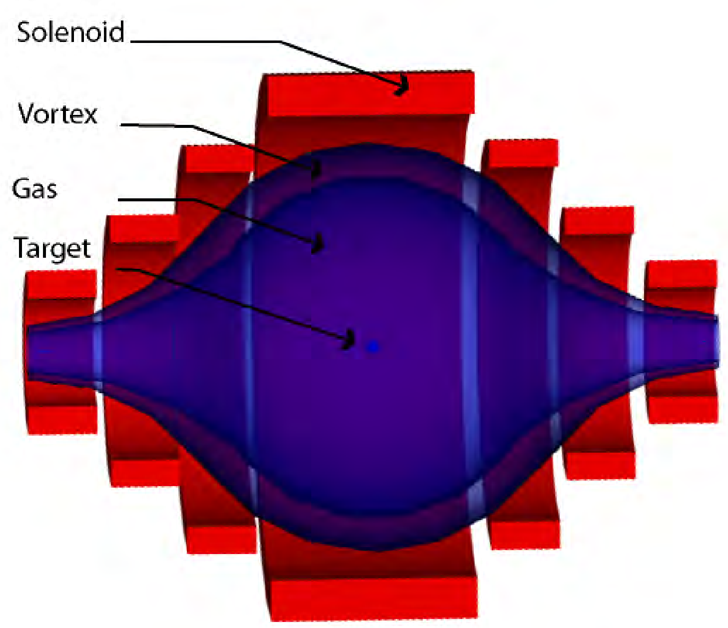
1000 μs exposure time

If surface-renewal frequency is 1 kHz, 2MW/m^2 is possible with a surface temperature 50°C greater than bulk temperature

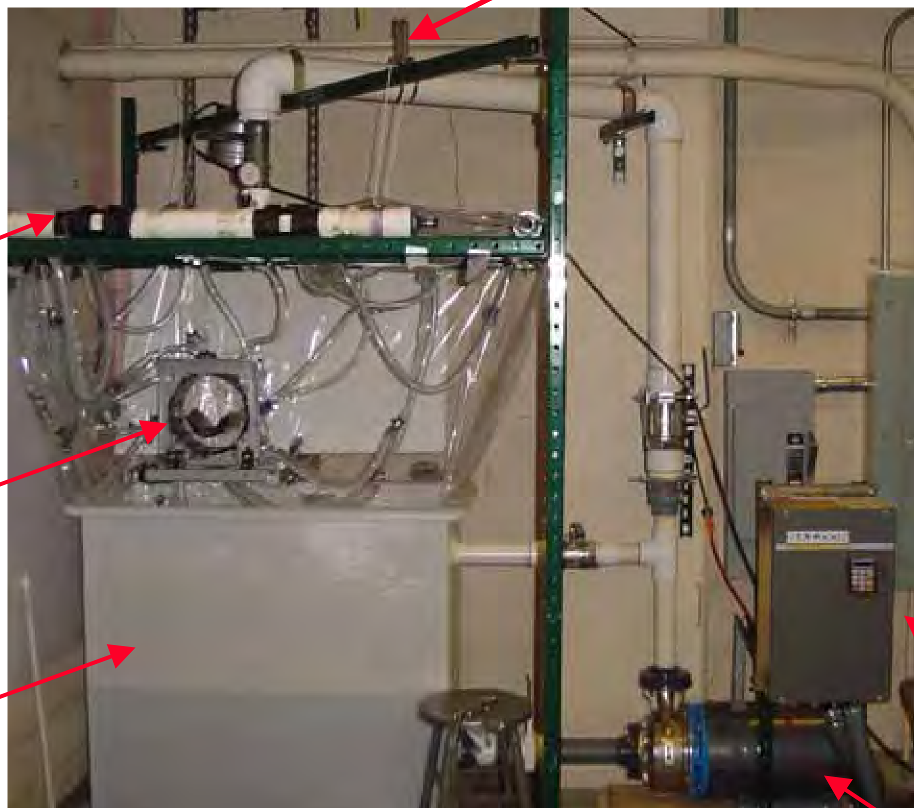
U.C. Berkeley

Modular solenoid HIF chamber could potentially use a large-scale vortex flow

- **Issues:**
  - **Using injection and suction to maintain vortex flow on substrate with non-uniform radius**
  - **Response of liquid layer to x-ray ablation (surface waves, substrate stresses, droplet ejection)**
  - **Effects of turbulent surface renewal on surface temperature and condensation**



A large variable recirculation flow loop is now running



- Pump is rated for 500-gpm at 300-ft of head
- Thanks to the frequency controller, the flow rate can be accurately varied between 0 and ~4000-gpm

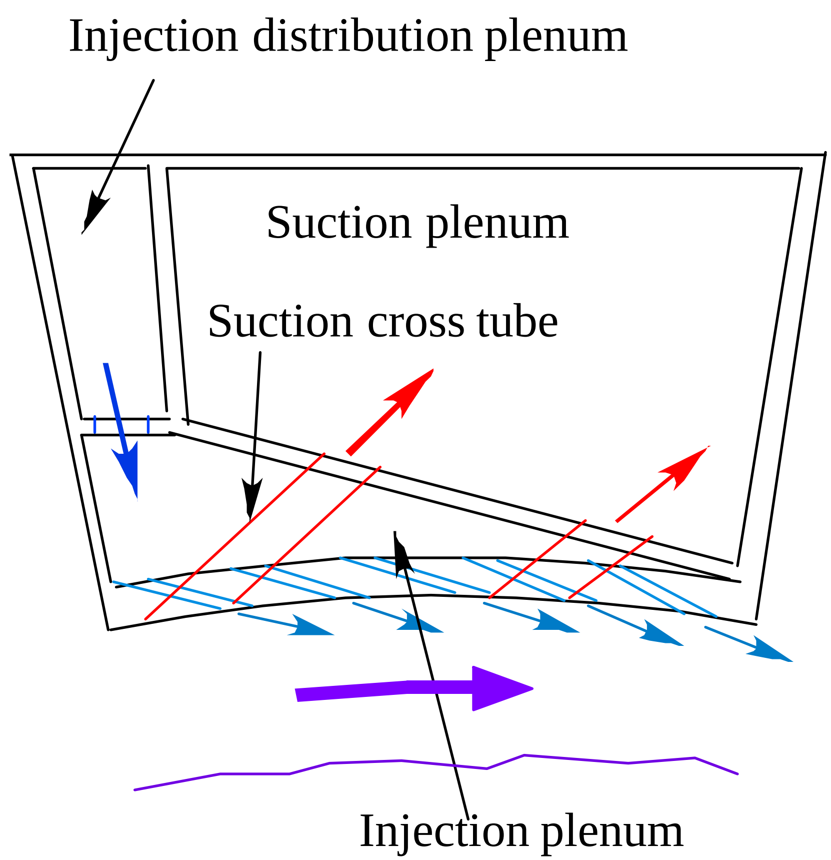
Based on earlier large vortex experiments new modular nozzles have been developed

- **the new modular nozzle system uses 8 to 12 interchangeable modules**

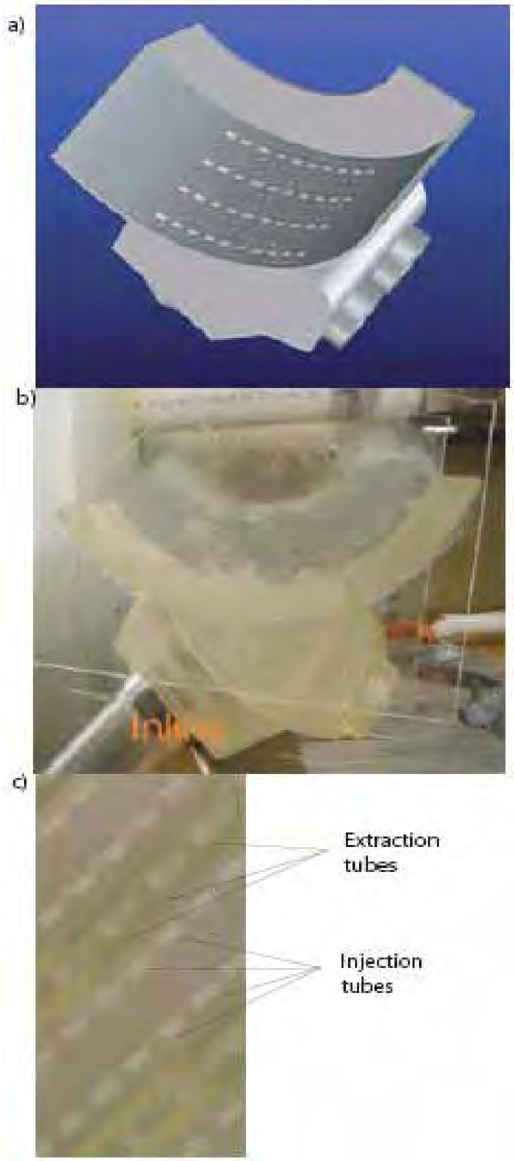
  to study the influence of the injection and suction angles

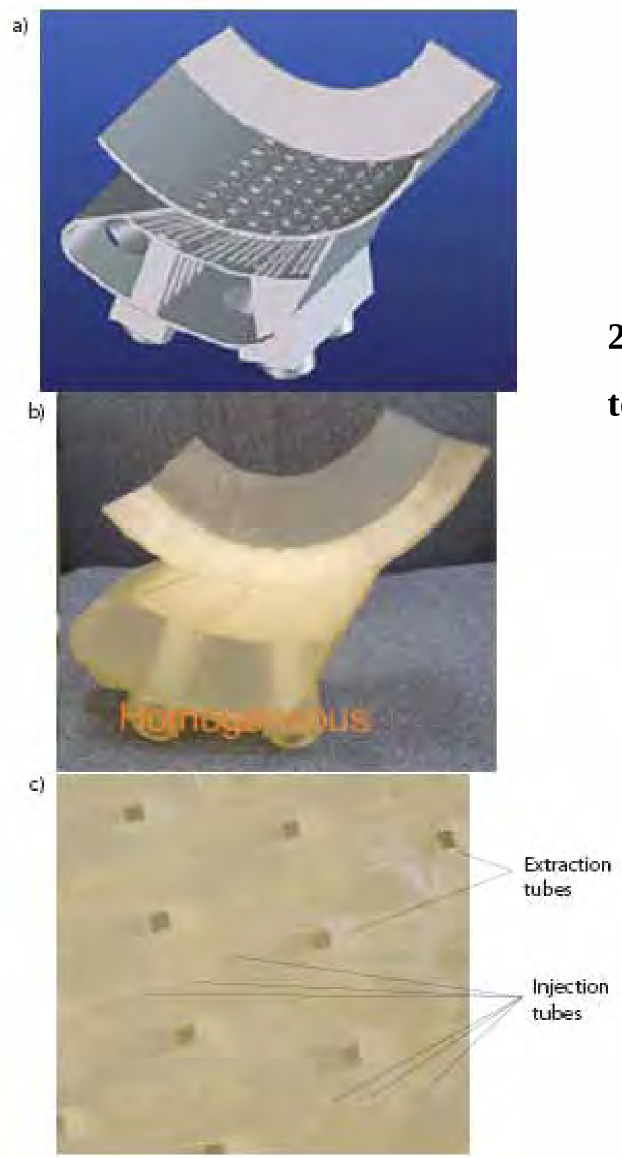
  the injection will be homogeneously distributed over the circumference

- **the modules were built with rapid prototyping**



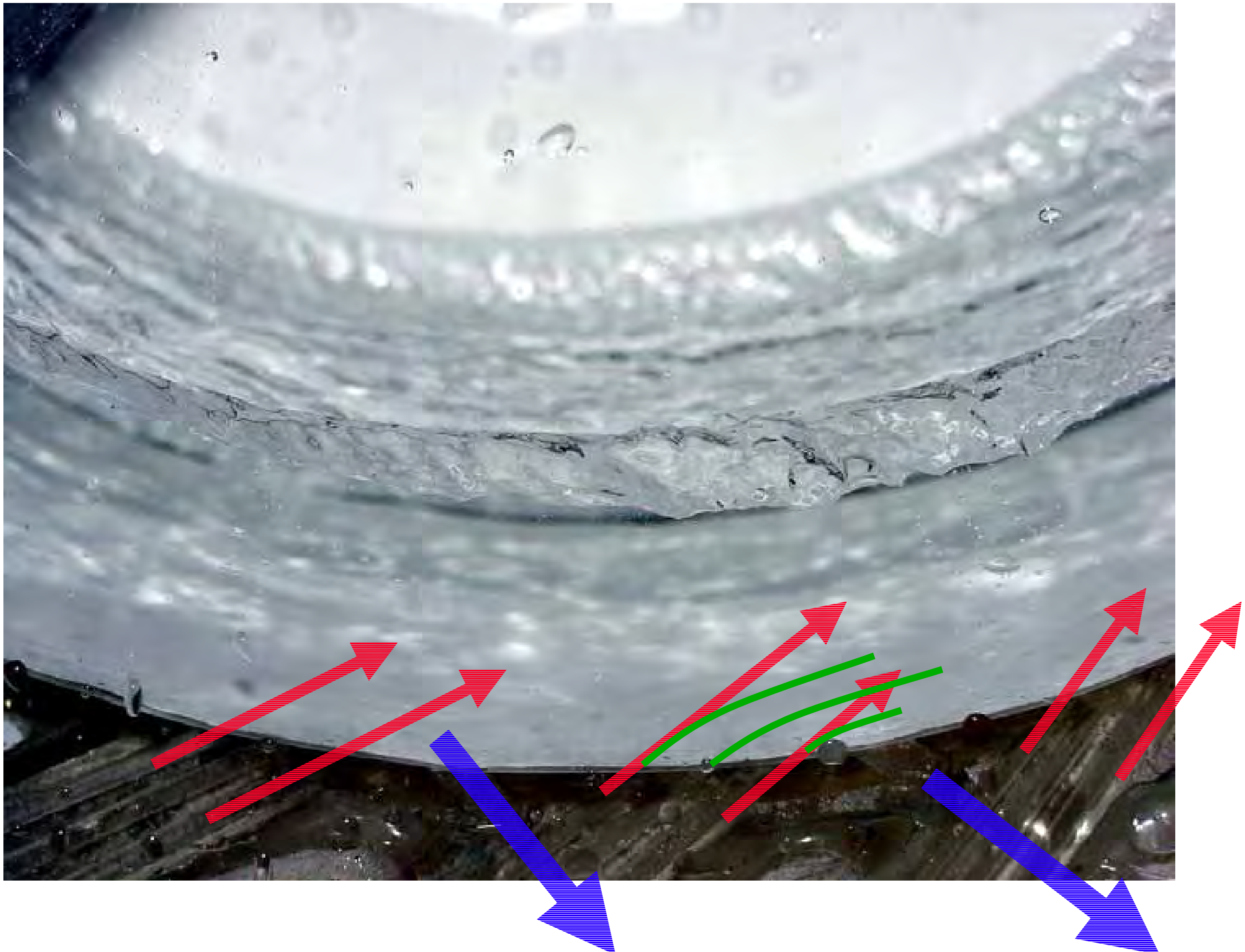
The Current Large Vortex Experiment



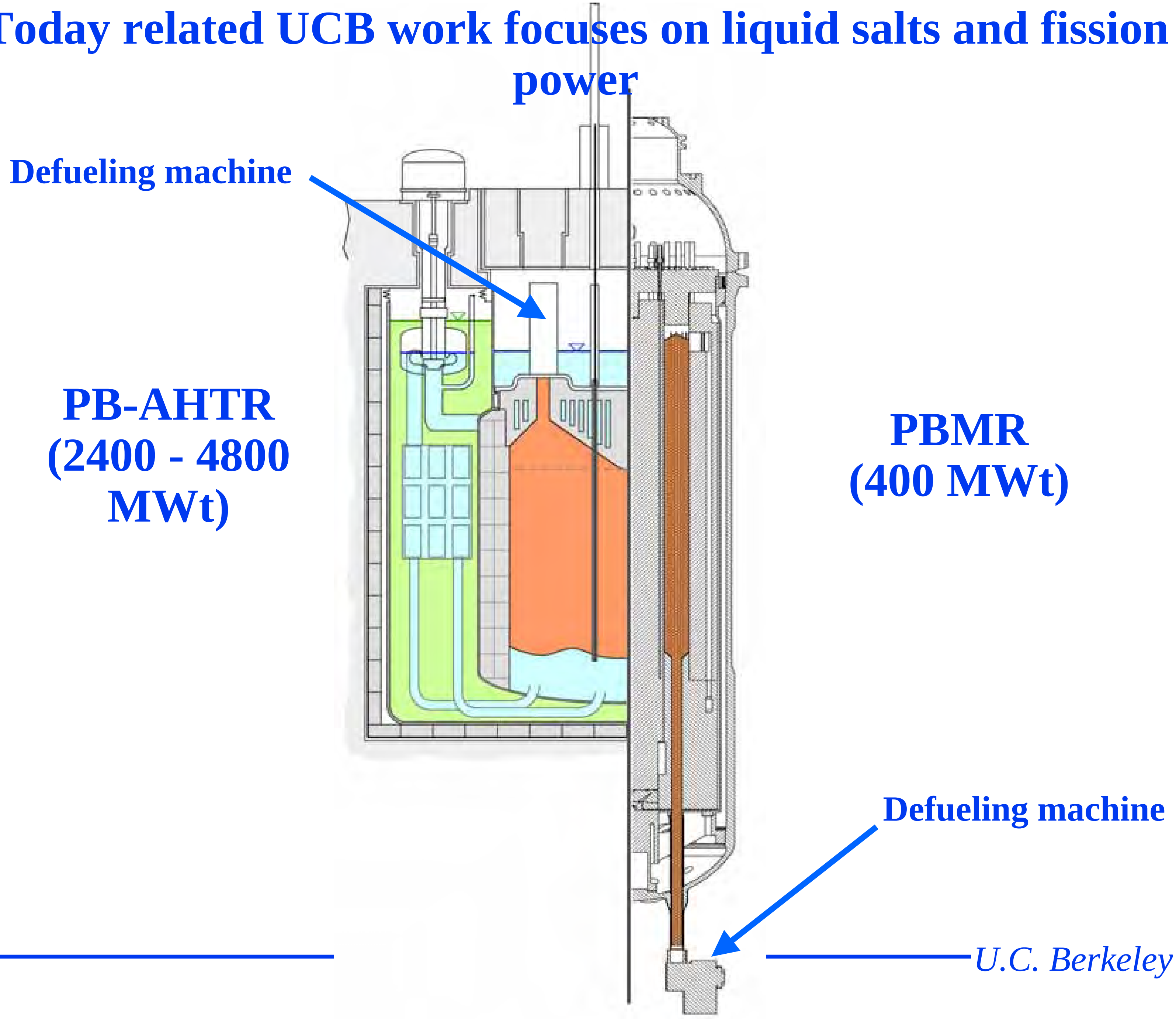


2 different geometries to study

The current Large Vortex Experiment focuses on studies of a partial section

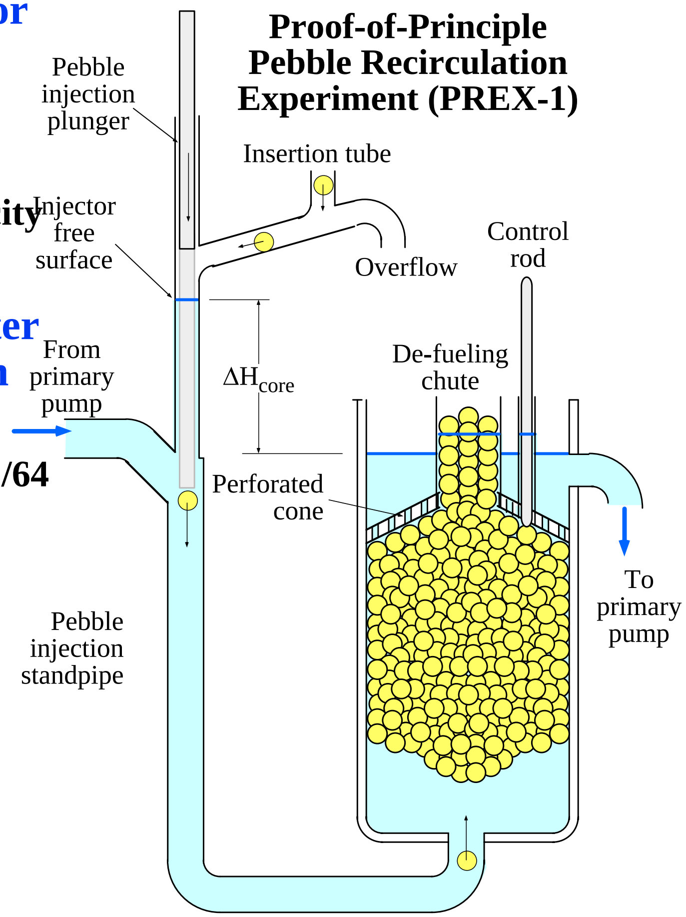


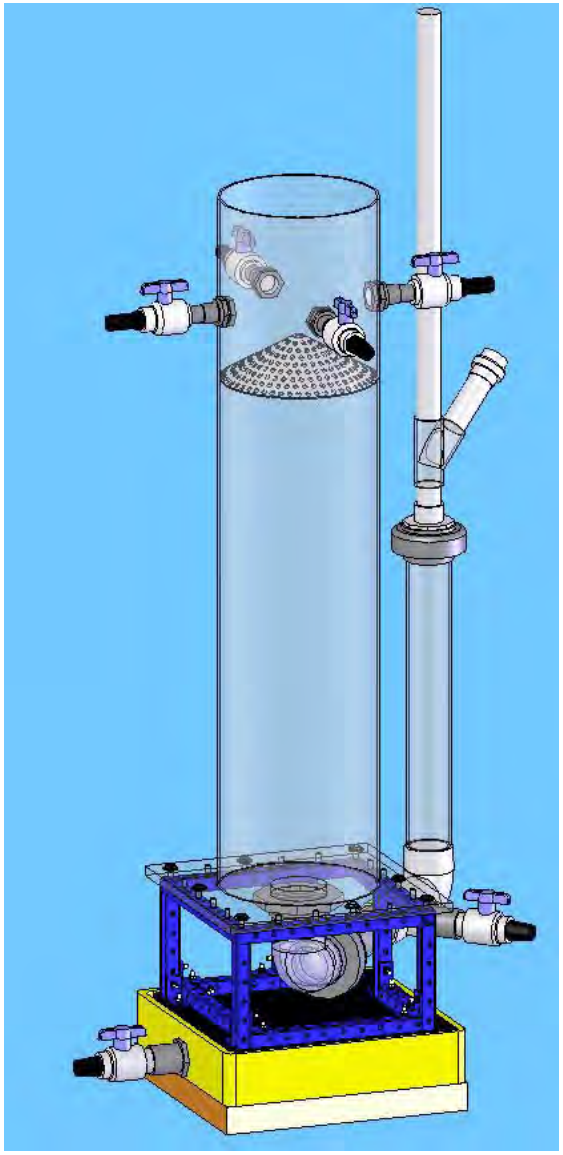
Today related UCB work focuses on liquid salts and fission power



The Pebble Recirculation Experiment (PREX-1) has demonstrated fission pebble recirculation

- **PREX reproduces the major phenomena required for pebble recirculation**
  - **injection**
  - **pebble terminal rise velocity**
  - **pebble bed dynamics**
- **PREX uses 2.54-cm diameter polypropylene spheres with water**
  - **1/2 length scale pebbles, 1/64 area bed, matches:**
    - » **Reynolds number**
    - » **Froude number**
    - » **pebble/salt density ratio**

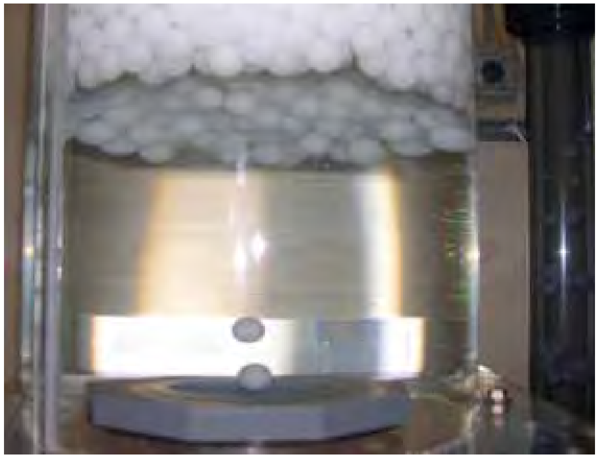




PREX-1 initial operation in October, 2006

PREX-1

Manual Defueling



Pebbles Entering

Pebble Injection
Into Cold Leg

Conclusions

- Substantial progress has been made in understanding thick-liquid IFE chamber response
- Vortex flows are interesting and have substantial promise
  - Potential for very high surface heat fluxes
  - Issues:
    - » droplet ejection from surface
    - » effects of ablation impulse loading
    - » control of flow for complex geometries
- Fission provides an interim technology
  - develop and qualify materials
  - molten salt heat transfer fluids
    - » materials compatibility
    - » target debris recovery
  - helium Brayton cycle power conversion
  - tritium safety and management
  - Can fusion systems burn further the pebbles from the fission plants?

Dry Wall Chambers for a Laser IFE Power Plant

A. R. Raffray
University of California, San Diego

and the HAPL Team

Inaugural IFE Science & Technology Strategic Planning Workshop

San Ramon, CA

April 24-27, 2007

Outline

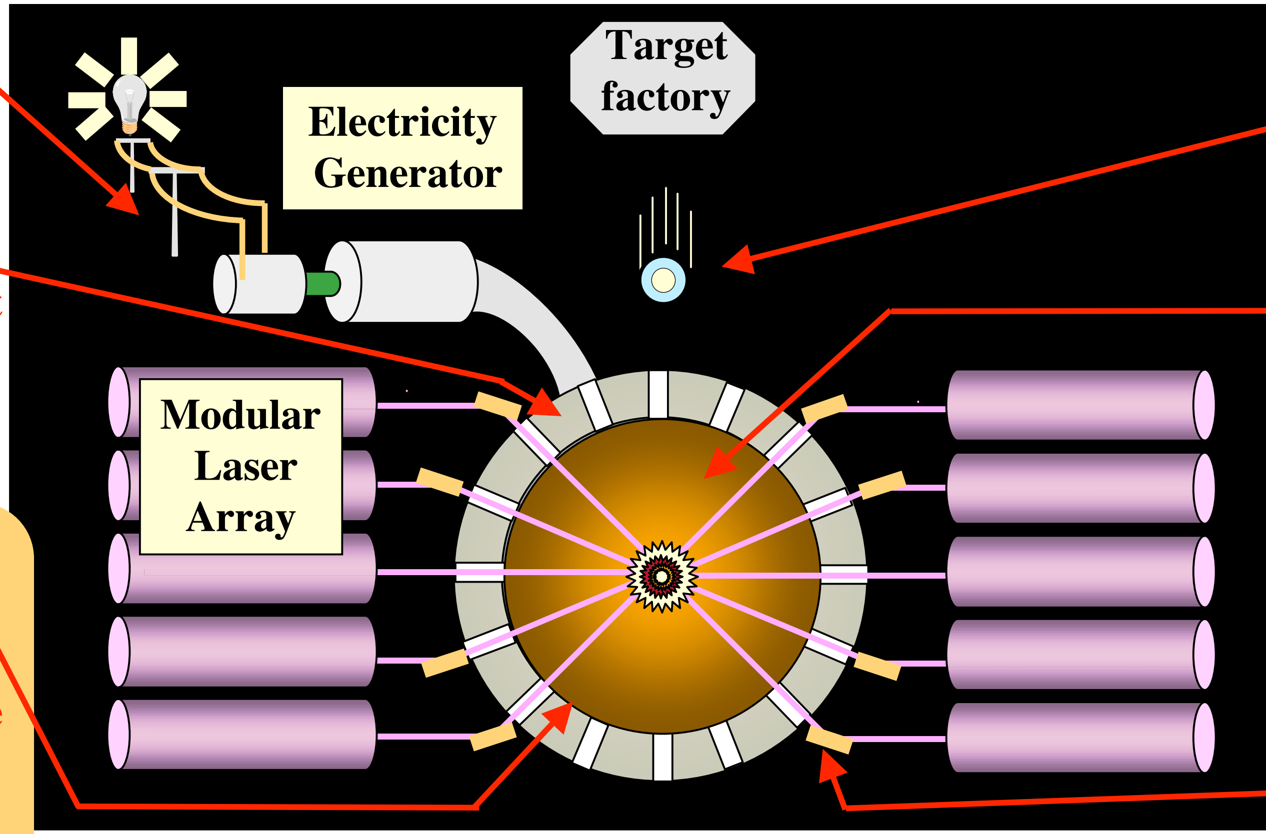
- **HAPL Program: Laser IFE with Dry Wall Chamber**
- **Threats and Key Issues for Dry Wall Chambers**
- **R&D Effort**
  - **Experiments**
  - **Modeling**
- **Alternate Chamber Concepts**
- **Conclusions**

The HAPL Program Aims at Developing a New Energy Source: IFE Based on Lasers, Direct Drive Targets and Dry Wall Chambers

System (including power cycle)

Blanket (make the most of MFE design and R&D info)

Dry wall chamber (armor must accommodate ion+photon threat and provide required lifetime)



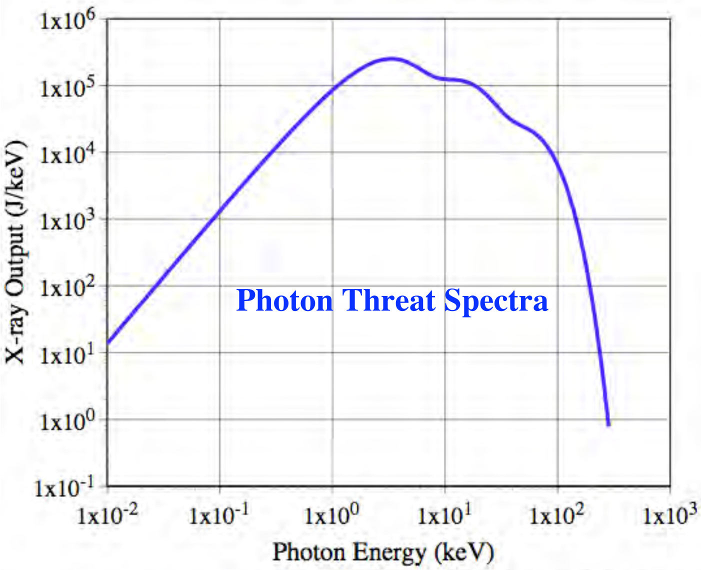
Target injection, (survival and tracking)

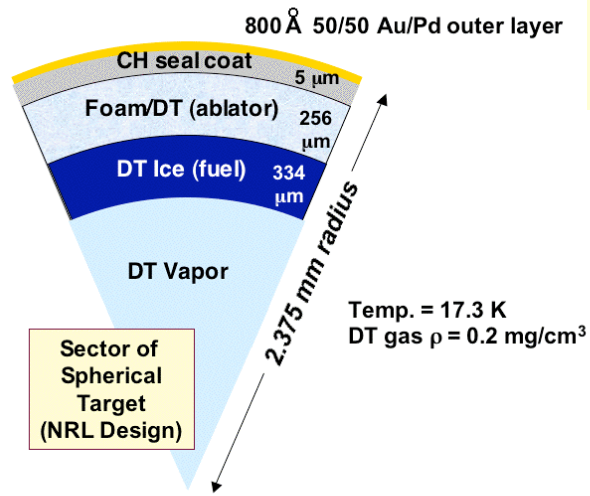
Chamber conditions (physics)

Final optics (+ mirror steering)

- Modular, separable parts: lowers cost of development AND improvements
- Conceptually simple: spherical targets, passive chambers
- Builds on significant progress in US Inertial Confinement Fusion Program

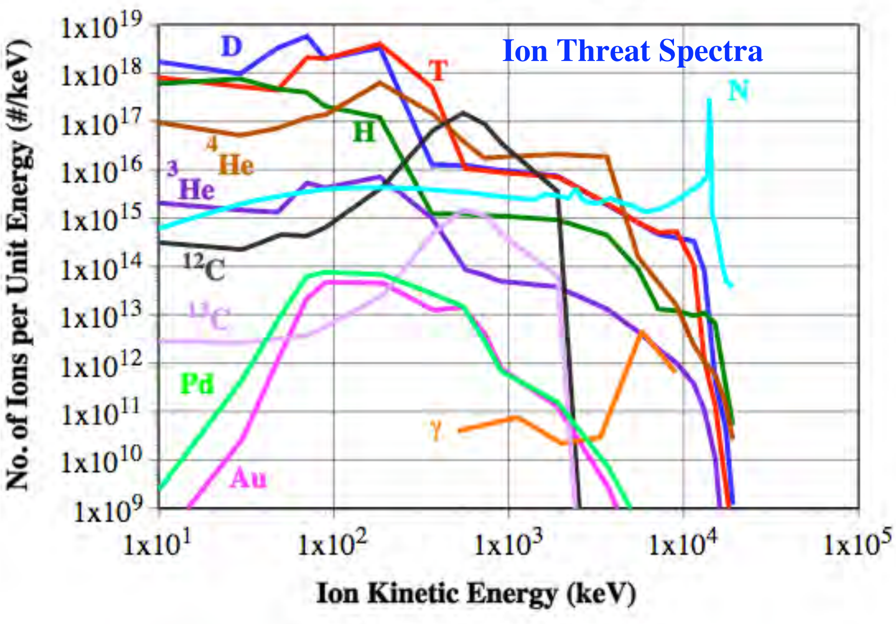
Chamber Wall Must Accommodate Threat Spectra from Direct Drive Target





Example 350 MJ direct drive target

	Direct Drive Target (MJ)
X-rays	4.94 (1.3%)
Neutrons	274.3 (74.7%)
Gammas	0.017 (0.005%)
Burn Product Fast Ions	47.14 (12%)
Debris Ions Kinetic Energy	40.71 (16%)
Total	367.1

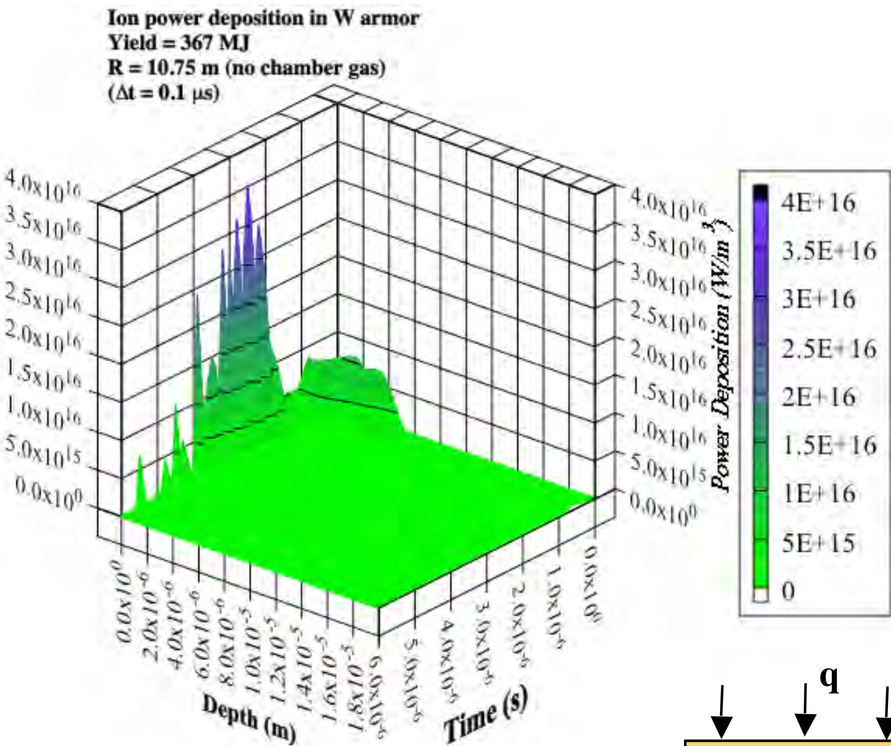


- X-ray, ion and neutron fluxes to the chamber wall several times per second.
- Neutron flux penetrates deeper and not an issue for armor.
- Need to develop dry wall armor that can accommodate X-ray and (more importantly) ion threats.

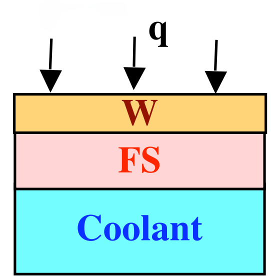
UCSD

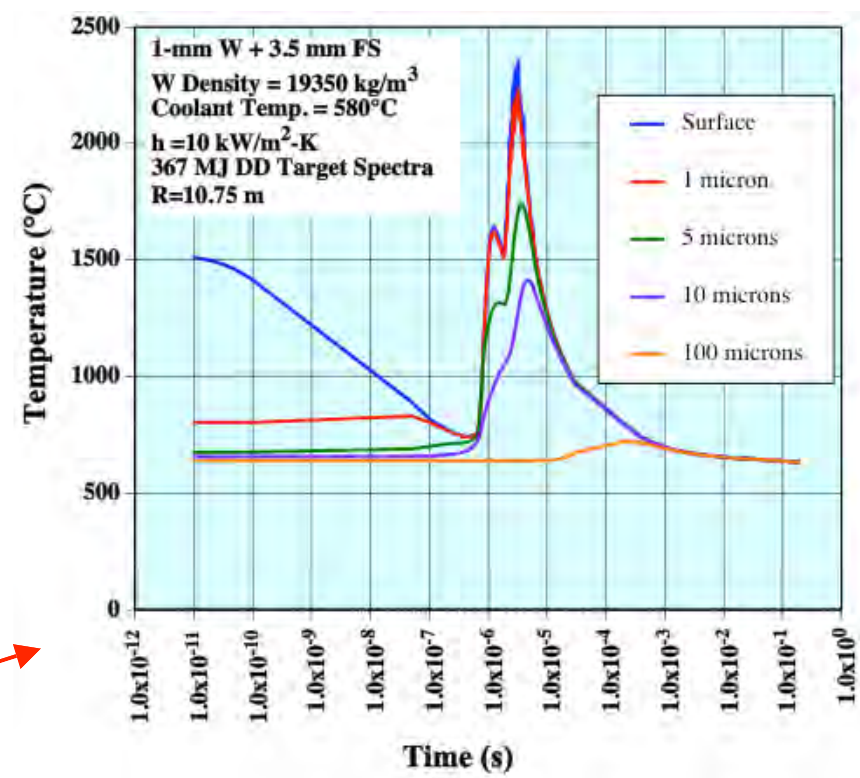
Power Deposition Occurs in a Very Thin Armor Region

Example power deposition profile in W armor for 350 MJ class direct drive target and 10.75 m chamber radius



- Only thin armor region sees huge temperature transients
- This led to the configuration choice of a thin armor layer (~ 1 mm) on a FS substrate
- Blanket at the back sees quasi steady state (can make use of MFE effort)
- W chosen as preferred armor material (high-temperature capability, no tritium concern)
- However, lifetime is a key issue and is the focus of the R&D in this area

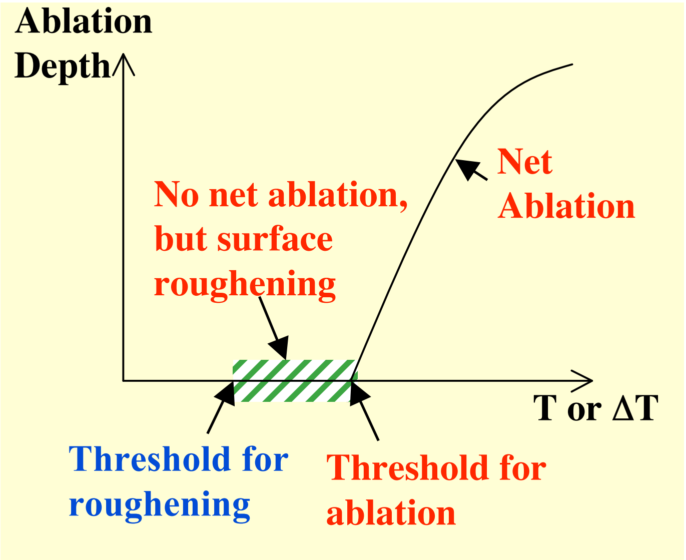




Example temperature history at different spatial location in W armor

W Armor Lifetime

- Several possible mechanisms could lead to premature armor failure:
  - ablation
  - melting (is it allowable?)
  - surface roughening & fatigue (due to cyclic thermal stresses)
  - accumulation of implanted helium
  - fatigue failure of the armor/substrate bond



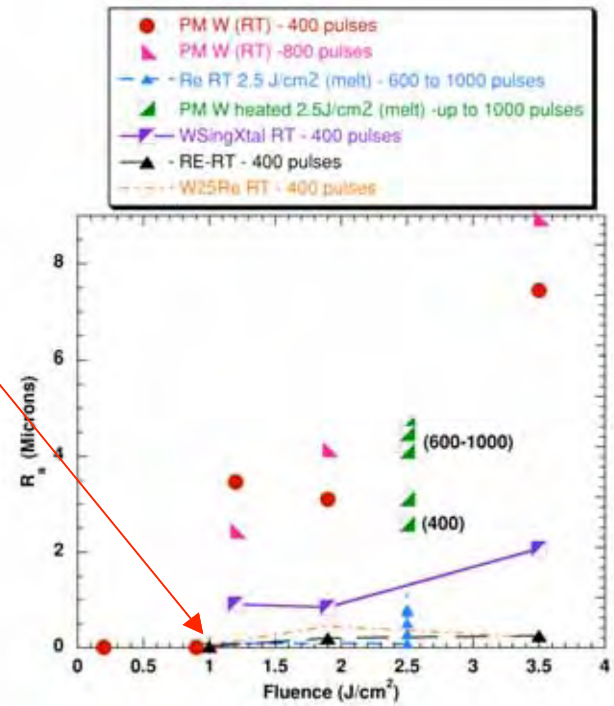
- R&D effort includes modeling and experimental testing of the armor thermo-mechanical behavior.

- Because the exact IFE ion and X-ray threat spectra on the armor cannot be duplicated at present, experiments are performed in simulation facilities:
  - Ions (RHEPP)
  - X-ray(XAPPER and Z)
  - Laser (Dragonfire)
  - Fatigue testing of the W/FS bond in ORNL infrared facility (initial results show good adhesion of 0.1 mm W diffusion bonded or plasma-sprayed on FS after 1000's of thermal cycle pulses).
  - He management is addressed by conducting implantation experiments (UNC/ORNL, UW) along with modeling of He behavior in tungsten (UCLA).

- The possibility of utilizing an engineered porous armor is also considered to help in enhancing the transport of implanted helium and in accommodating thermal stresses.

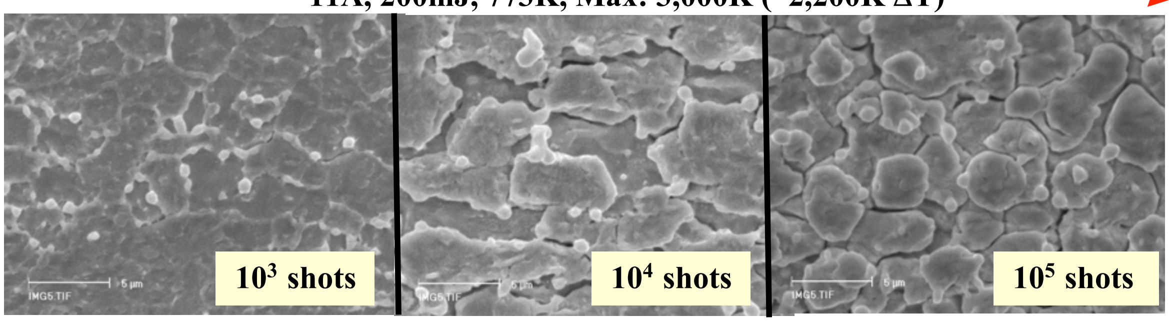
Long Term Exposure Experiments Suggest Roughening Threshold and Temperature Dependence for W, for example:

- **Results from the RHEPP ion beam facility at SNL (0.8-1.6 MeV) indicates roughening threshold for powder metallurgy W (PM W) at ~ 1 J/cm² at RT.**
  - **some improvement with heated W samples.**
  - **single crystal W better than PM W**
  - **rhenium (Re) and Re/W alloy much better.**



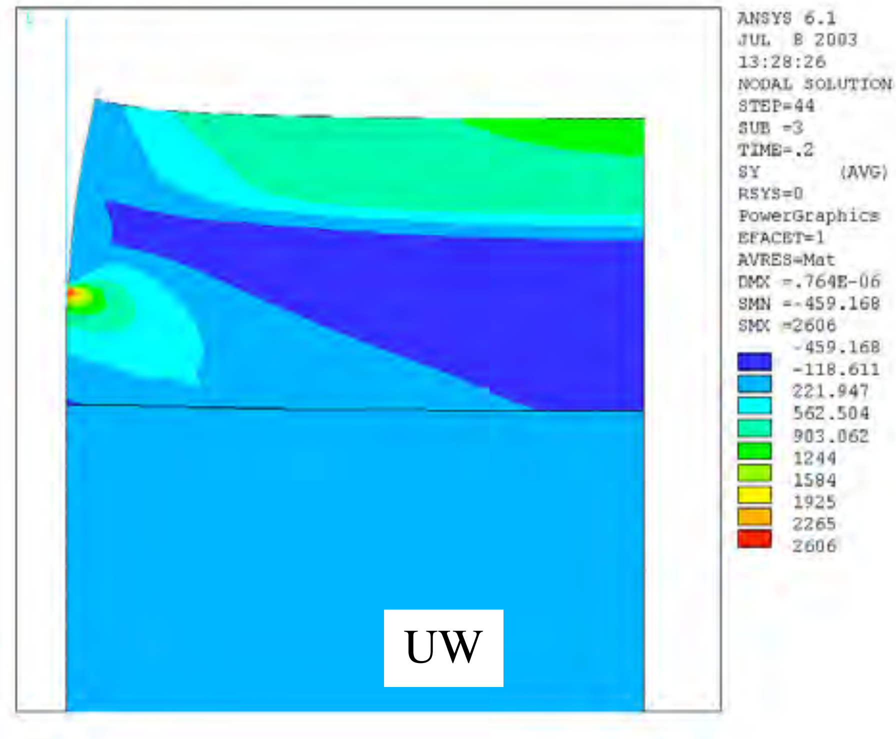
- **Initial results from Dragonfire laser testing facility at UCSD (YAG laser, 10 Hz) with W (~3000°C) indicate possible roughening saturation after ~10^5 shots.**
- **Also, PM W behavior seems to depend more on T than ΔT.**

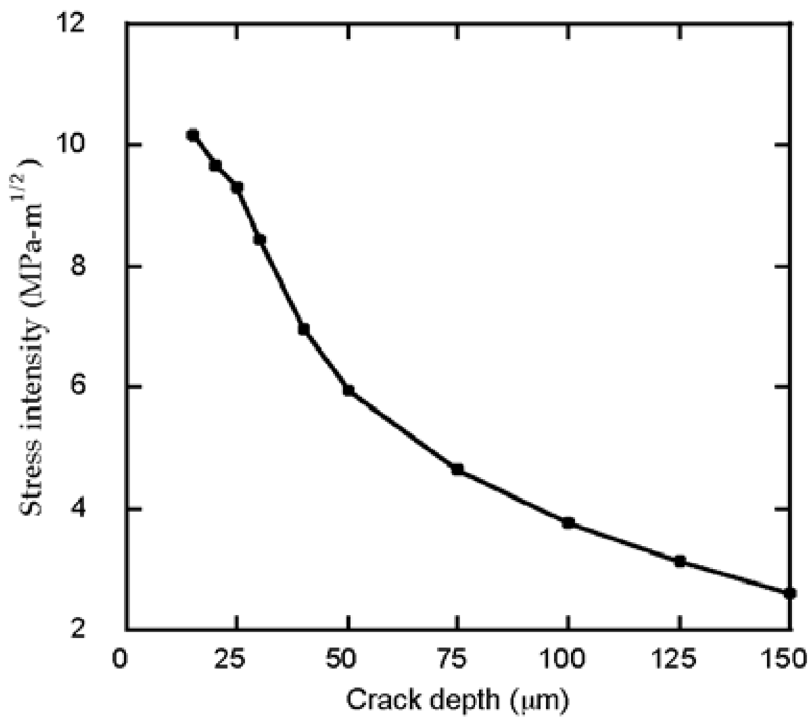
11A, 200mJ, 773K, Max: 3,000K (~2,200K ΔT)



- **Does roughening matter if it does saturate and does not lead to armor failure? Probably not.**
- **Additional testing and diagnostics needed for confirmation of initial experimental indications on saturation and threshold for W armor.**
- **For HAPL, as an initial armor survival constraint from these early results, a temperature limit of 2400°C was assumed for the W armor (e.g. corresponding to a RHEPP fluence of ~1.2 J/cm²).**
- **Based on all experiments, ~1500°C is min. upper limit below which nothing is observed.**

Example of Modeling Performed to Better Understand the W Thermal Stress Behavior and Crack Initiation and Growth





- **ANSYS calculations of the stress intensities for crack depths ranging from 15 μm to 150 μm (and spacing of 1 mm)**
  - **The stress intensity falls from ~10 MPa-m$^{1/2}$ for the 15 μm crack to ~2.6 MPa-m$^{1/2}$ for the 150 μm crack, and to zero for deeper cracks with smaller spacings.**
  - **This indicates that cracks that initiate at the surface may stop before reaching the armor/steel interface (within ~100 μm from the surface).**
  - **Limited fracture mechanics data for thin tungsten films make prediction of fracture behavior is difficult (must rely on experiments).**

He Studies Focused on Investigating He Retention and Surface Blistering Characteristics of W

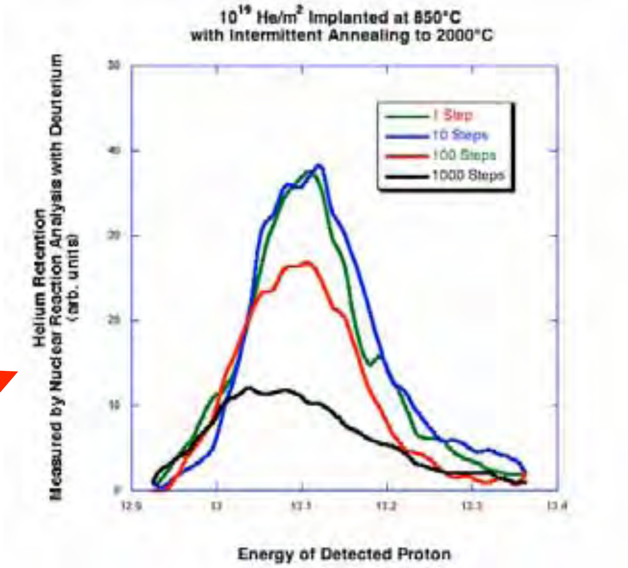
- **Goal is to determine if He retention can be mitigated by the pulsed nature of He implantation in combination with the high temperature spikes within the IFE reactor**

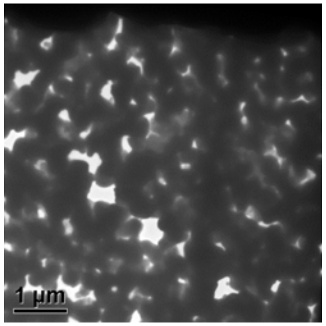
- **Experimental activities:**
  - He implantation/anneal cycle experiment (ORNL+UNC)
    - ~850°C base T, ~1.3 MeV He, pulsed implantation and anneals at 2000°C over ~ 1000 cycles to fluences of ~10^{20} He/m^2

  - He + D implantation in Inertial Electrostatic Confinement (IEC) facility (UW)
    - ~800°C base T, ~10-100 keV ion, pulsed implantation to fluences of ~10^{22} He/m^2

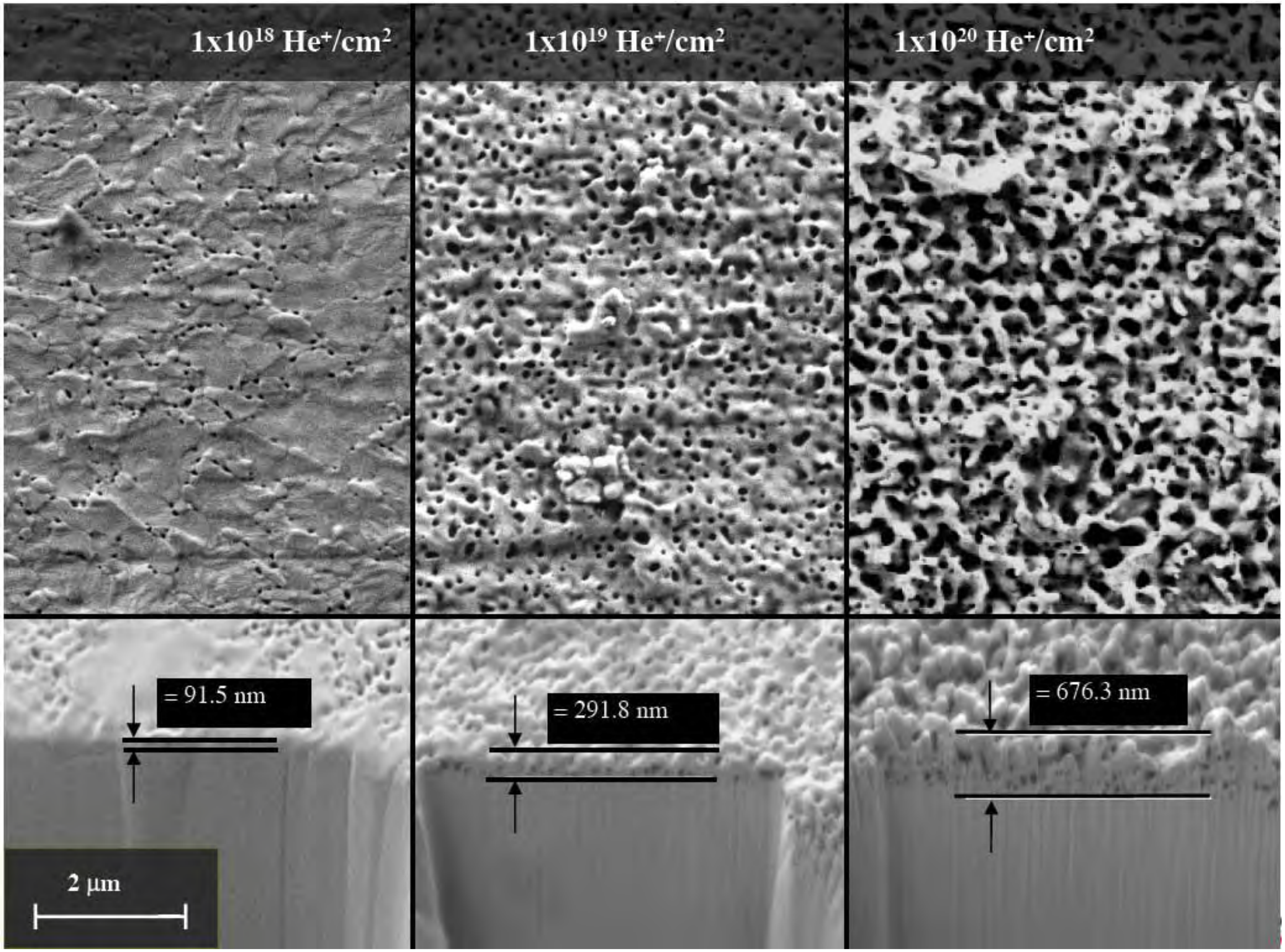
- **Modeling activities:**
  - HEROS code (UCLA)

- **Engineered material also considered to enhance He release and provide stress relief**
  - e.g. vacuum plasma spray porous W with ~10-100 nm microstructure (PPI/UCSD)



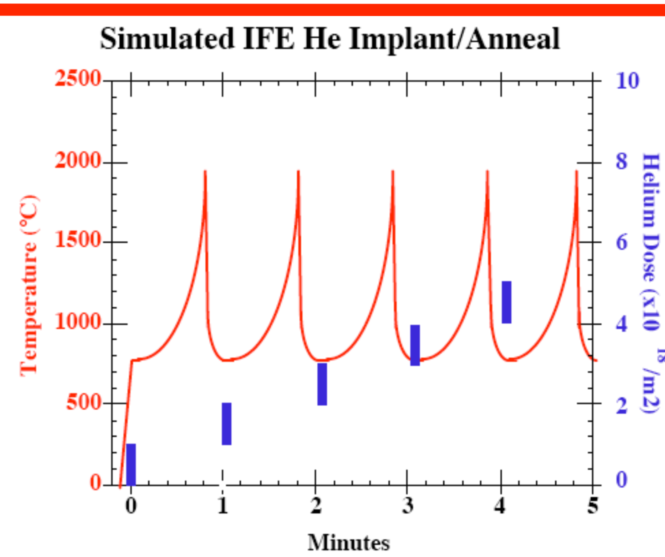


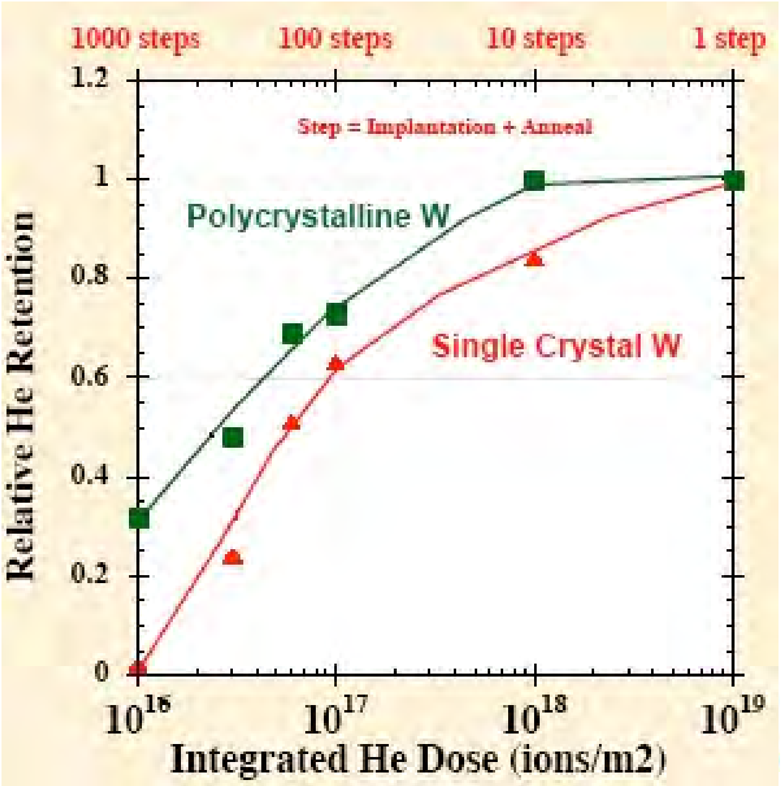
Helium Ion Irradiation of W at 800 °C in IEC Facility at UW Shows Significant Surface Damage at Modest Exposures



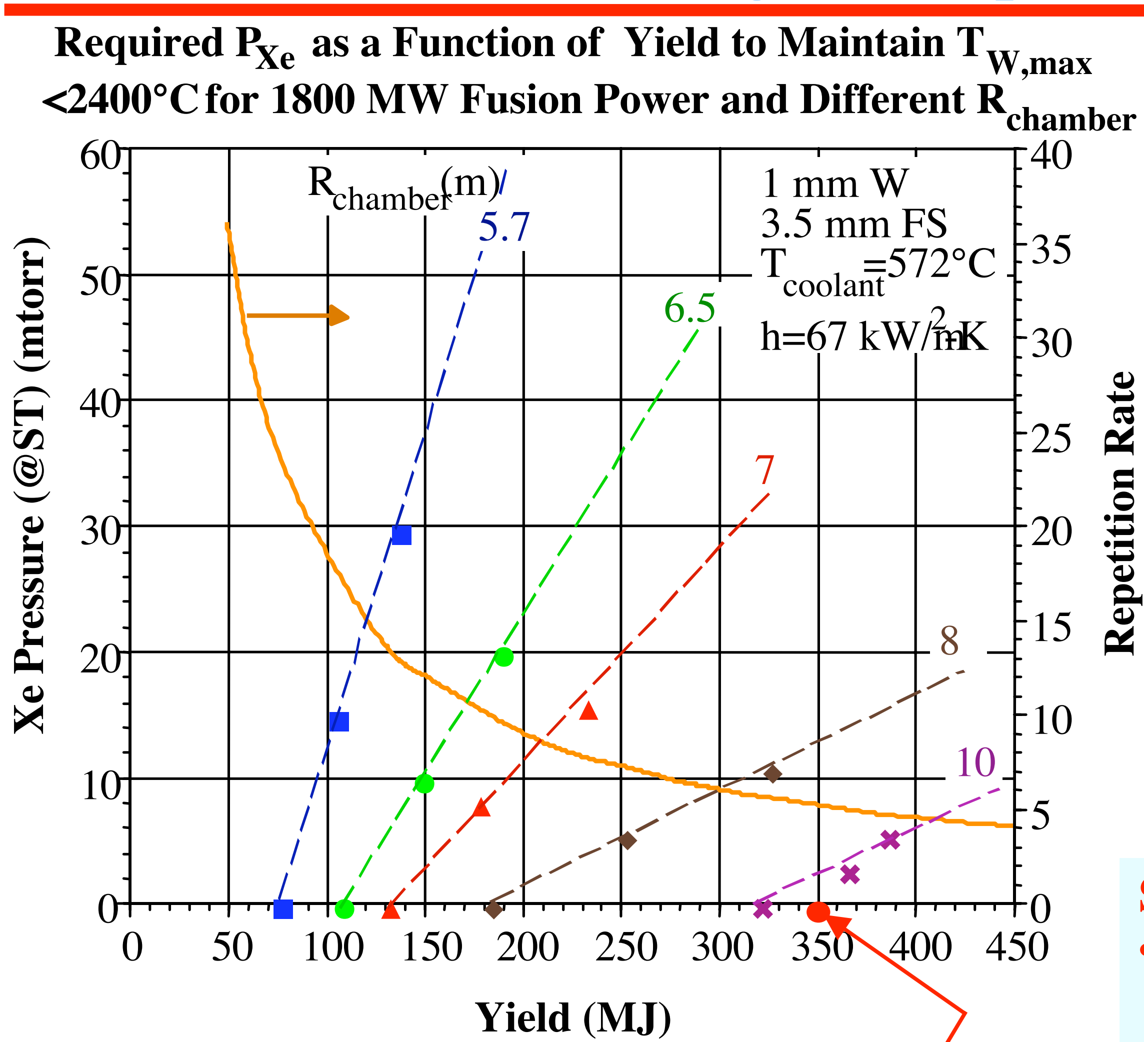
IFE Conditions May Mitigate He Retention Effect

- He retention decreases drastically when a given He dose is spread over an increasing number of pulses, each one followed by W annealing to 2000°C, to the extent that there would be no He retention below a certain He dose per pulse.
- For SC, this threshold would be ~ 10^{16} ions/m^2 per shot (lower for PC W)
- This threshold is still too low as the IFE He dose per shot is ~10^{17} ions/m^2.
- However, for the IFE case the W armor surface temperature would be closer to 2400°C which would significantly increase the He mobility and should increase the per-shot threshold.
- Thus, the trends are promising but more R&D is required to make a better assessment of He behavior in the IFE case.





Armor Survival Constraints Impact the Overall IFE Chamber Design and Operation



- **W temperature limit of 2400°C assumed for illustration purposes (~1.2 J/cm^2 roughening threshold from RHEPP results)**
- **Limit to be revisited as R&D data become available**
- **Desirable to avoid protective chamber gas based on target survival and injection considerations --> leads to large chamber**
- **Armor failure due to He implantation still a concern**

- **Example chamber parameters for 0 gas pressure:**
  - **Yield = 350 MJ; R=10.5 m; Rep. rate ~ 5 for 1750 MW fusion**

CA

Strategy:

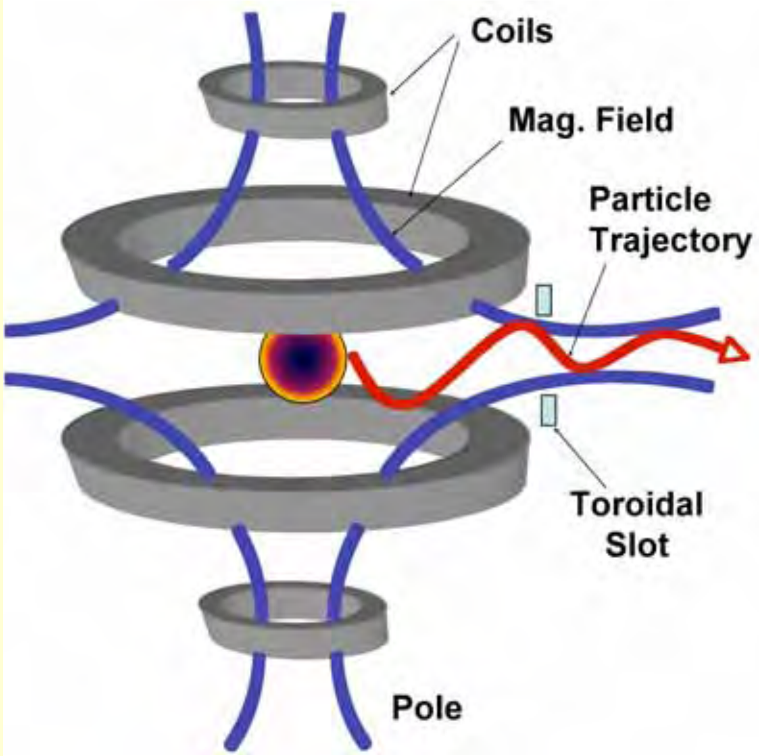
- **Maintain large chamber as baseline but look at advanced options that would reduce the ion threat spectra on the armor and allow for more compact chambers.**
  - **Magnetic intervention is such an option**

Magnetic Intervention: Utilizing a Cusp Field to Create a Magnetic Bottle Preventing the Ions from Reaching the Wall and Guiding them to Specific Locations at the Equator and Ends

- **Utilization of a cusp field for such magnetic diversion has been experimentally demonstrated previously**
  - **1980 paper by R.E. Pechacek et al.,**

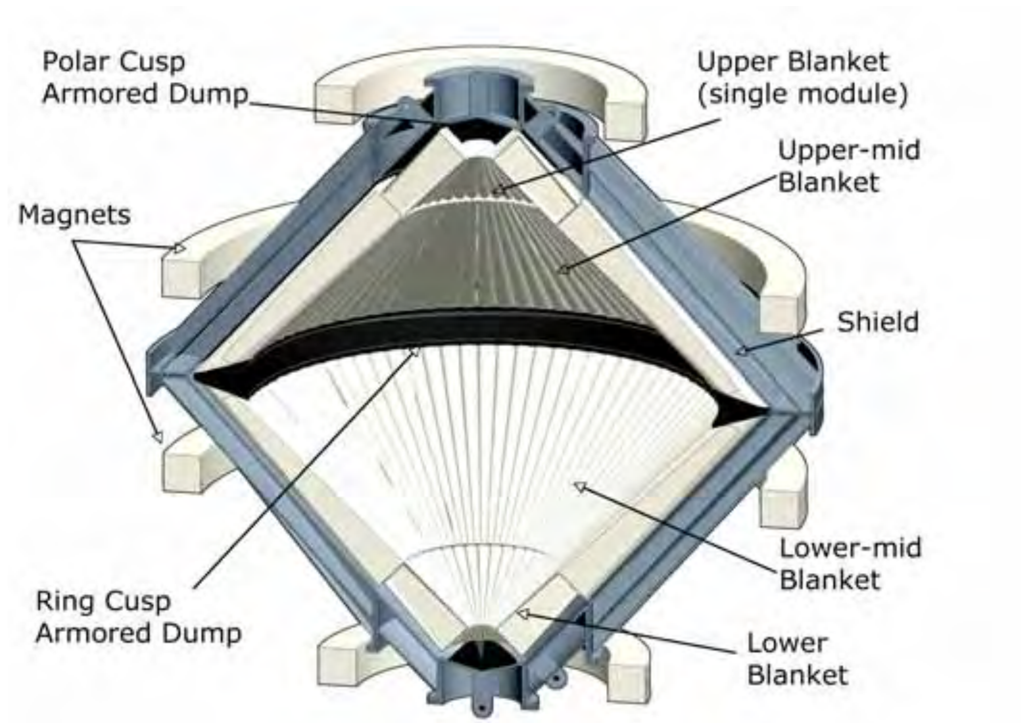
- **Following the micro-explosion, the ions would compress the field against the chamber wall, the latter conserving the flux. Because of this flux conservation, the energetic ions would never get to the wall.**

- **One possibility would be to dissipate the magnetic energy resistively in the FW/blanket, which reduces the energy available to recompress the plasma and reduces the load on the external dumps**
  - **about 70% of ion energy dissipated in blanket**
  - **about 30% of ion energy in dump region**



Conical Chamber Well Suited to Cusp Coil Geometry and Utilizing SiC_f/SiC for Resistive Dissipation

- **Armored ion dumps could be inside the blanket chamber (as schematically shown) or outside, which is the preferred configuration allowing for easier maintenance.**
- **SiC_f/SiC blanket with liquid breeder (see poster).**
- **Water-cooled steel shield (~0.5 m thick) required to protect the coil (behind the blanket or around coil).**
- **Design provides for accommodation of laser ports.**
- **For a 6 m radius chamber, the temperature spike from the photon energy depositon is ~300°C in the SiC FW.**

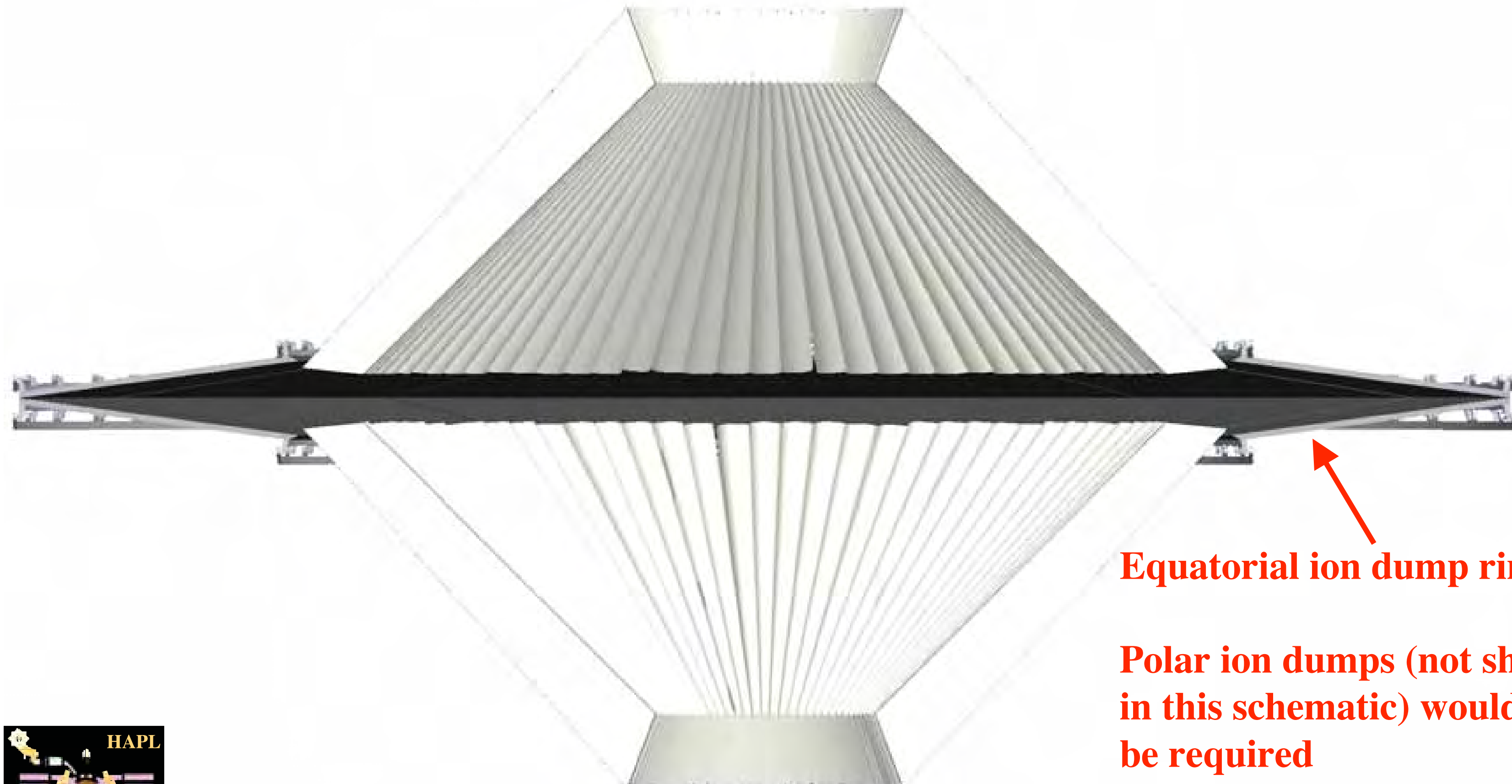


- **Preferred design includes an external vacuum vessel with maintenance performed from the top.**

Advantageous to Position Dump Plates Outside Blanket Chamber

- **Ions trapped within magnetic bottle escaping at equator and poles**
  - **70% of ion energy as magnetic energy dissipation in blanket**
  - **30% of ion energy to dumps**

- **Duck bill configuration provides large surface area**
- **Could use W dry wall dump and allow melting**
- **Ion dump outside chamber allows for easier maintenance**

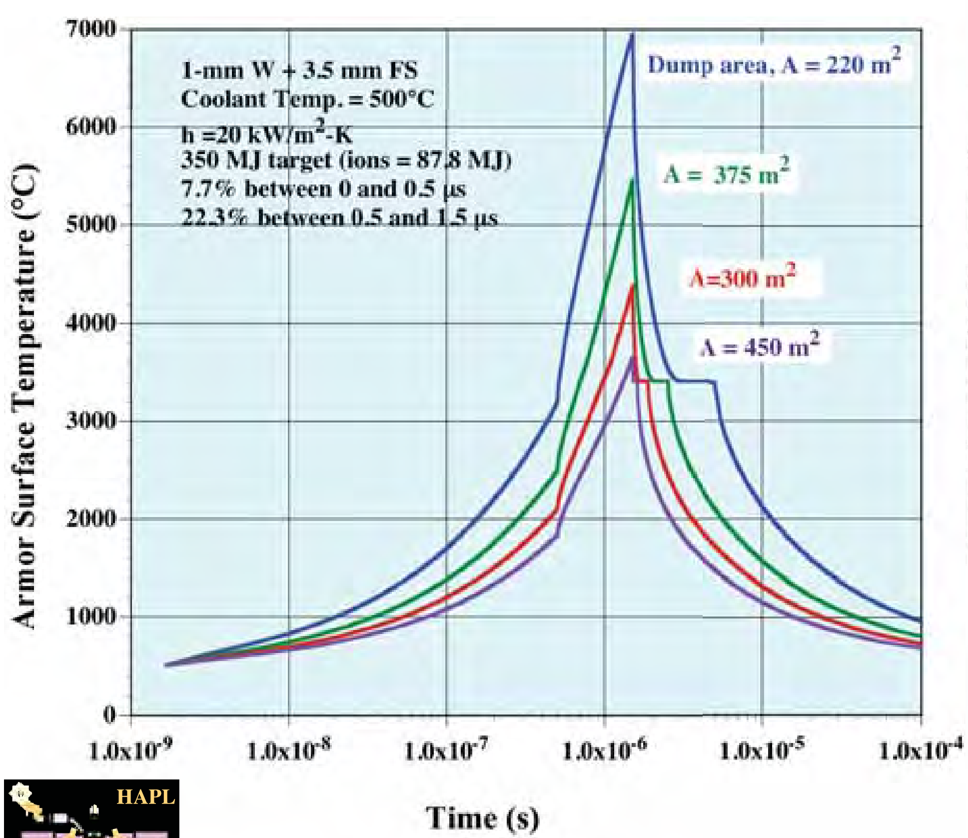


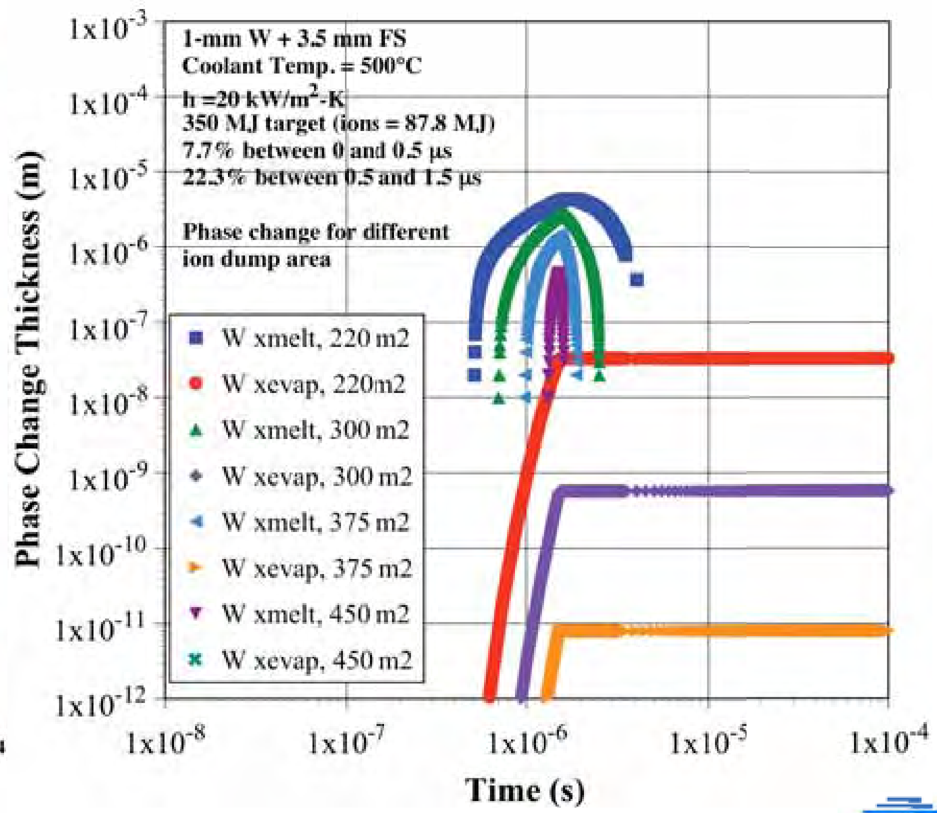
Equatorial ion dump ring

Polar ion dumps (not shown in this schematic) would also be required

Temperature and Phase Change Thickness Histories for Ion Dump with W Armor

- 350 MJ target (ion energy = 87.8 MJ)
- Heat flux scaled to ion dump area
- For ion dump area = 300 m^2 (e.g. R_{dump} ~ 9 m; L_{dump} ~ 2.7 m)
  - From 0 to 0.5 μs, q'' = 4.53×10^{10} W/m^2 (7.7% of ion energy)
  - From 0.5 to 1.5 μs, q''= 6.56×10^{10} W/m^2 (22.3% of ion energy)





Conclusions

- The HAPL program is aimed at developing Laser IFE based on a laser driver, direct drive targets and a solid wall chamber.
- The design and R&D effort in the chamber and material area is focused toward the key issues affecting the W/FS armor/FW survival under the ion and photon threat spectra.
- Armor testing shows promise, but there are still unanswered questions (He retention and thermomechanical damage)
- Magnetic diversion of ions in chamber is promising but requires more effort

Status of Developing the Target Supply for IFE

N. B. Alexander, L. Brown, D. Callahan, P. Ebey, D. Frey, R. Gallix, D. A. Geller, C. Gibson, J. Hoffer, J. Maxwell, A. Nikroo, A. Nobile, C. Olson, N. Petta, R. Petzoldt, R. Raffray, W. Rickman, G. Rochau, D. Schroen, J. Sethian, J. D. Sheliak, J. Streit, M. Tillack, E.I. Valmianski

Presented by Dan Goodin

at the

IFE Science & Technology Strategic Planning Workshop
San Ramon, CA
April 24-27, 2007

Main messages (conclusions) of this talk…….

1. ***IFE target technology builds upon the larger ICF program***
   - *FESAC - "tremendous leverage"*
   - *John Sethian - "shameless utilization"*

2. **Huge effort into NIF ignition target <u>and</u> expt's building to ignition**
   - Synergism fosters efficiency (e.g., foam shells)

3. **Most of the recent target technology progress has been on laser fusion targets**
   - Brief status of HIF and ZFE targets will be presented….

4. **For laser fusion - all the major process steps have been identified**
   - Ongoing work for each step is a near-term laboratory <u>demonstration</u> of feasibility supporting IFE

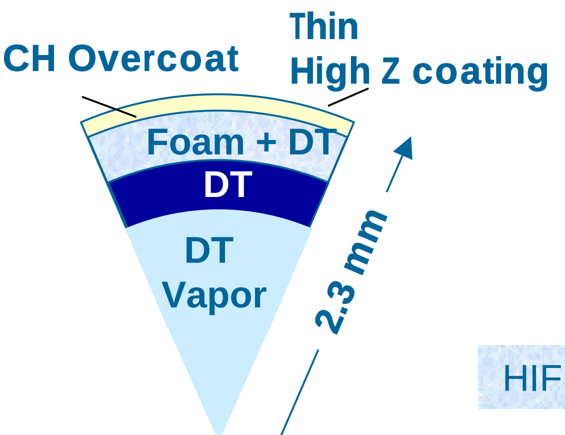
Good progress has been made on the HAPL demonstration programs….

Target development is an essential component of any IFE plan....

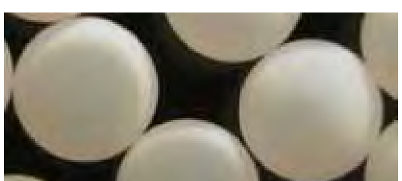
- **Three main IFE concepts**
  - Strong synergism but key differences that lead to specific technologies

Laser Fusion

- **Foam capsule with overcoat**

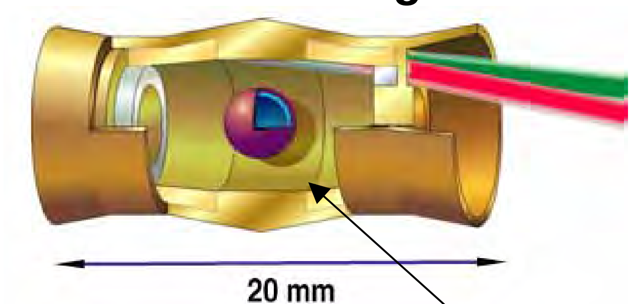


NRL High Gain Target

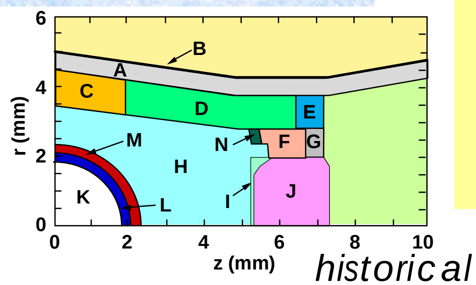


Heavy Ion Fusion

- **Advanced manufacturing methods**



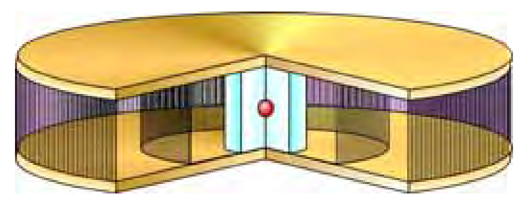
HIF Distributed Radiator



Low density metal foams

Z-Pinch IFE (ZFE)

- **Emerging requirement's & concepts**



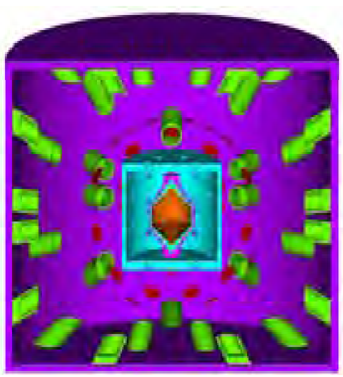
SNL Dynamic Hohlraum

Key = time for transport & loading

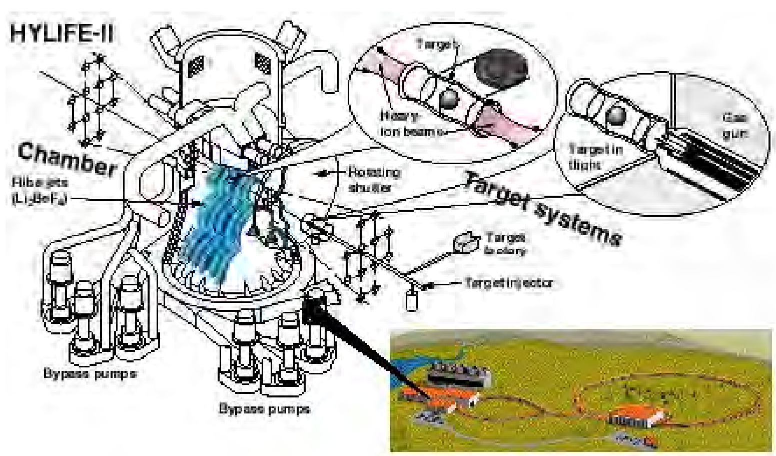
Top level target technology requirements

- **Basic requirements**
  - Supply about 500,000 targets per day for a ~1000 MW(e) laser fusion or HIF power plant (~88,000 for ZFE at 0.1 Hz, 10 chambers)
  - Do it cheaply, each laser fusion/HIF target has an energy value of about $3.00 ($22.50 for ZFE)

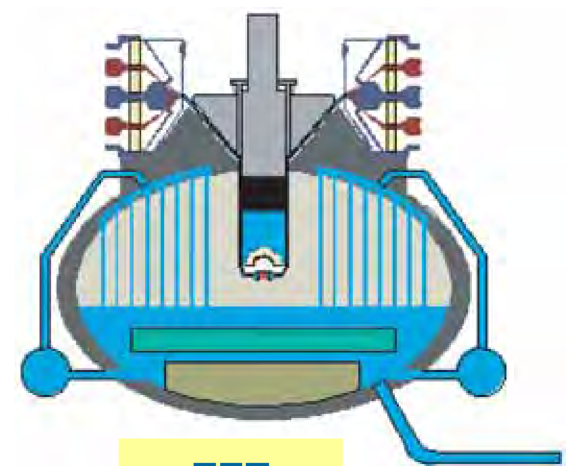
Specific target requirements have been defined to varying degrees…



SOMBRERO Laser Fusion



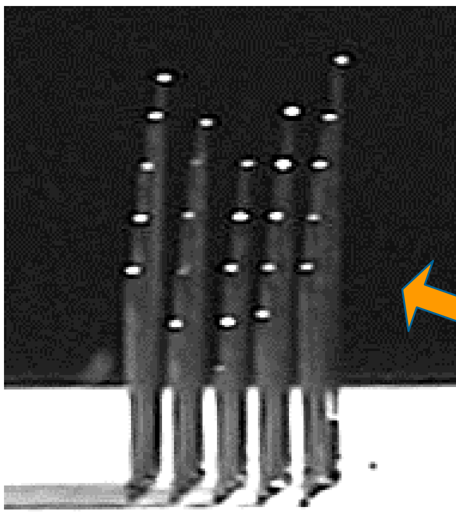
HIF - HYLIFE-II



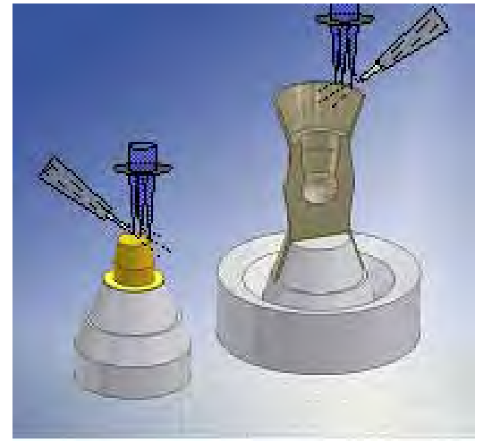
ZFE

HIF - laser-assisted chemical vapor deposition (LCVD) to manufacture the HIF hohlraum

- **Low-density, high-Z only materials needed**
- **Proposed concept - micro-engineered matl's**
  - Build from "inside out", avoid machining and handling low-density foam



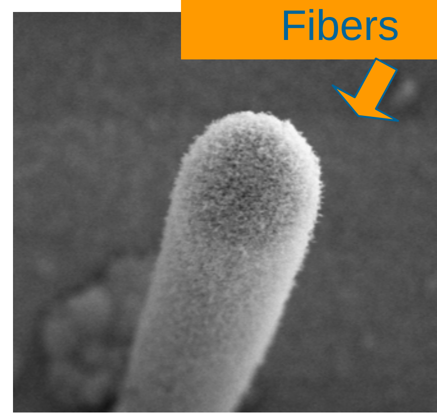
Arrays demo'd via Diffractive Optics; enables low-density blocks and engineered foams.



3D-LCVD hohlraum fabrication

Si-W Alloy Fibers

LCVD for alloys of normally immiscible materials (NIM's)

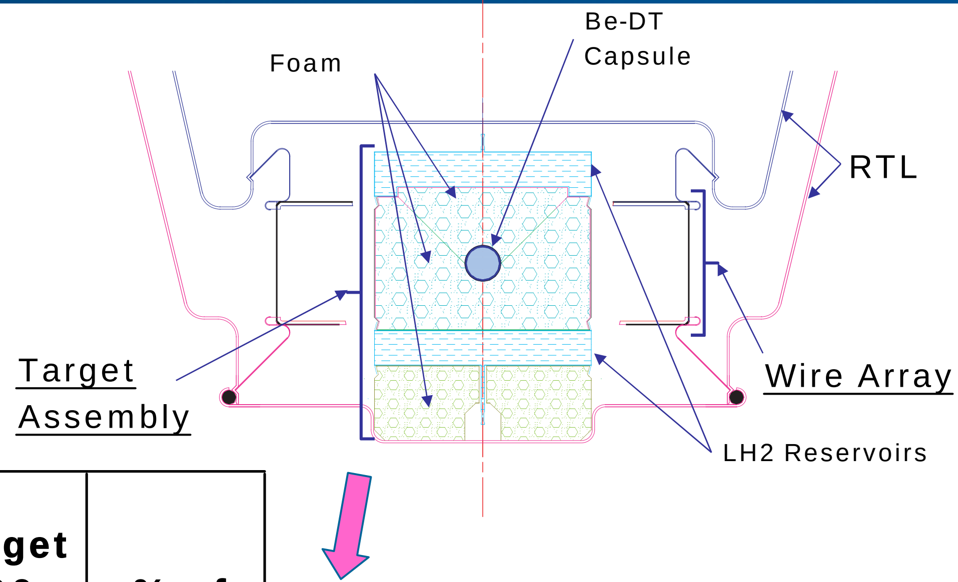


Goodin, D.T., et al, "Progress in Heavy Ion Driven Target Fabrication and Injection", Nuclear Instruments and Methods in Physics Research, A, Vol 544, 2005, 34-41,

Maxwell, James, et.al., A Process-Structure Map for Diamond-like Carbon Fibers from 1-Ethene at Hyperbaric Pressures, Advanced Functional Matl's, 15, 7, 2005, 1077-1087.

ZFE target conceptual design allows an initial cost comparison for all three concepts

- **ZFE "target load" has liquid hydrogen cooling buffers**
- **Allows temperature control during loading process**



IFE Target Cost Comparison

IFE Concept	Target Design	Target Yield (MJ)	Est'd Cost/target for 1000 MW(e)	% of E-value
Laser Fusion	Direct drive foam capsule	~400	$0.17	~6
HIF	Indirect drive distributed radiator	~400	$0.41	~14
ZFE	Dynamic hohlraum "target load"	~3000	$2.86	~13

Assumptions:
- development programs done
- n^{th}-of-a-kind plant
- does not include RTL

Goodin, D.T., et al, "A cost-effective target supply for inertial fusion energy", __Nuclear Fusion 44__ (2004), S254-265.

Outline of processes for the HAPL target supply

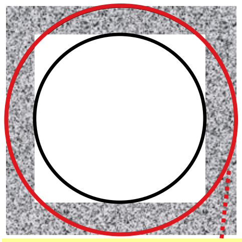
1) Fabricate foam capsules

Micro-encapsulation

QuickTime™ and a DV/DVCPRO - NTSC decompressor are needed to see this picture.

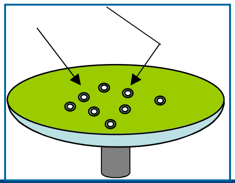
FTF-sized (2.4 mm OD) foam capsules

2) Overcoats



A) Interfacial reaction

B) GDP coating



C) Sputter coating of metal (Au/Pd)

Highly isothermal environment

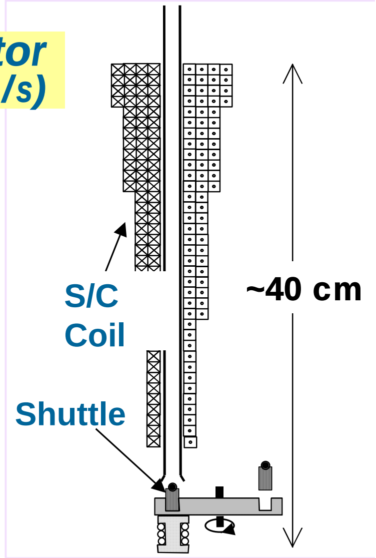
3) DT Fuel Layer

Layering cryostat

Fluidized bed

Accelerator (~50-100 m/s)

4) Inject Target



5) Track Target

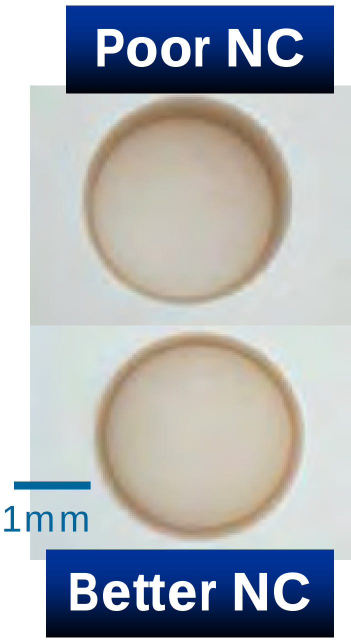
Optical systems

“glint” for tracking

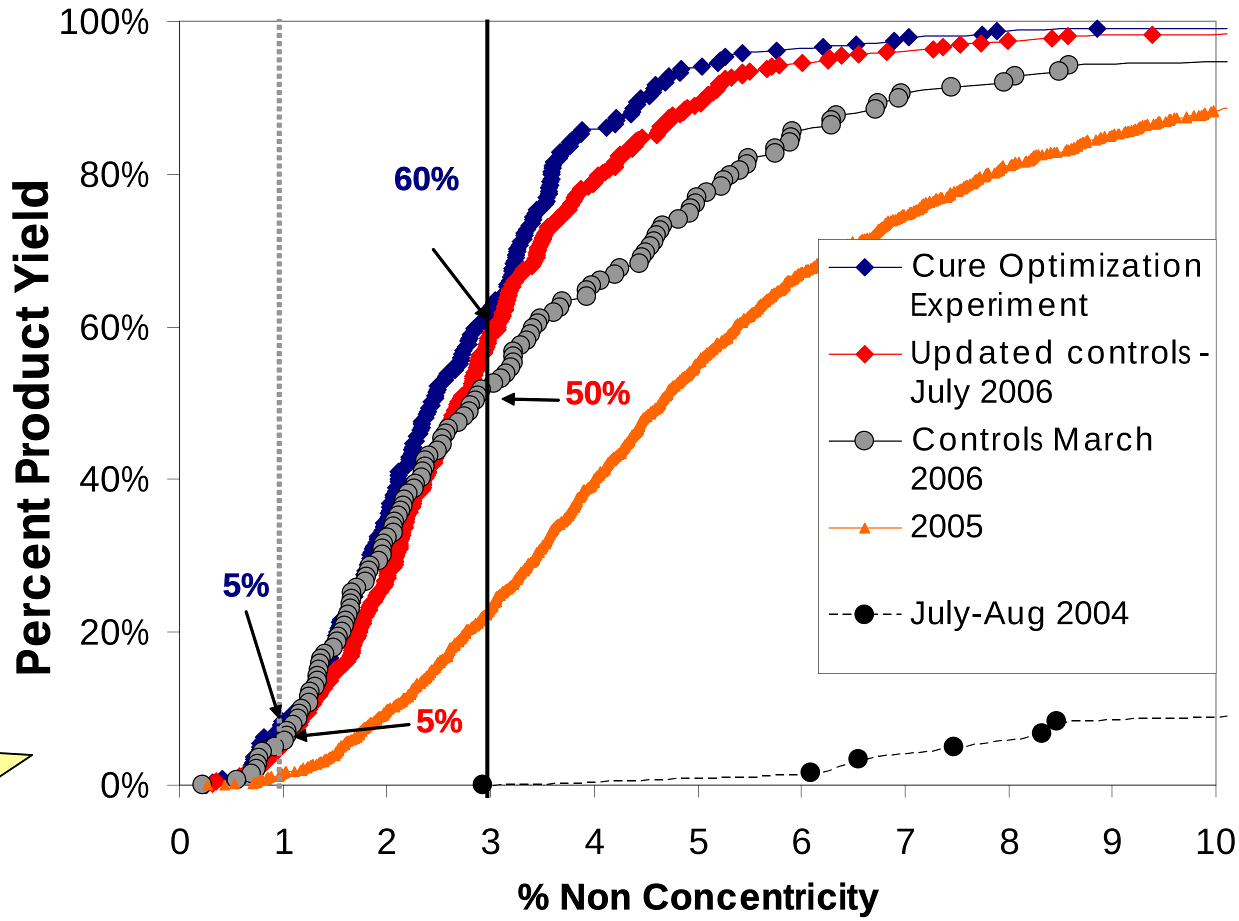
QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.

1) We can make the HAPL foam capsule

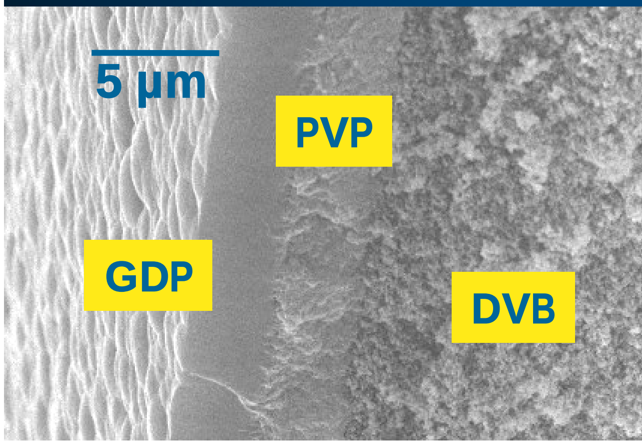
- **Systematic, parametric studies have led to ability to control capsule parameters (material, OD, wall thickness, sphericity, density……)**



Non-concentricity (NC) is a "wall uniformity" defect



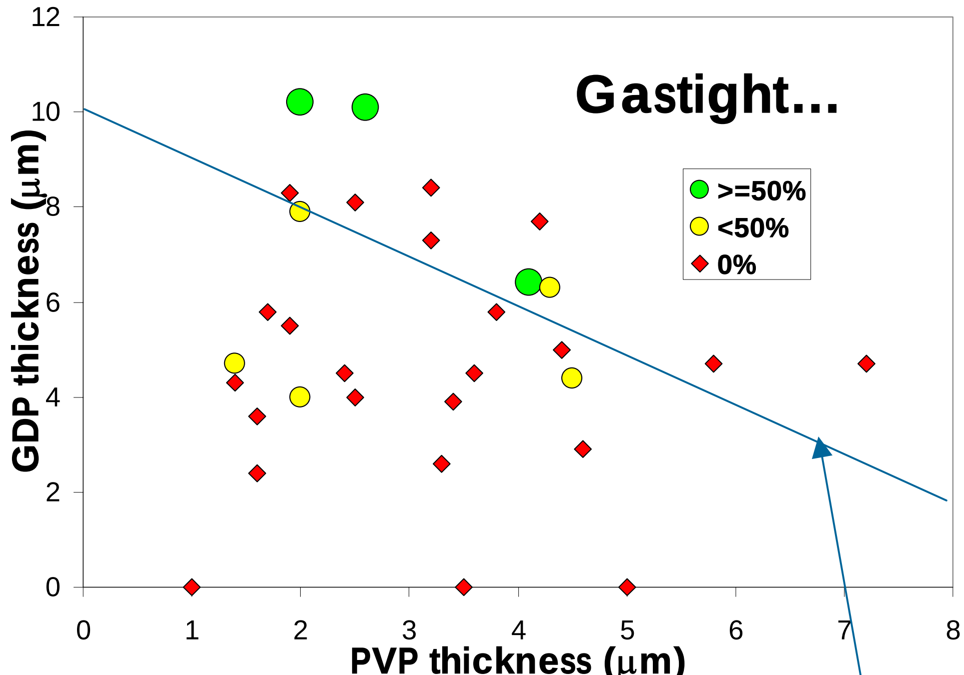
2) The capsule overcoat is a current R&D focus …



(PVP/GDP), Interfacial layer covers the larger pores, GDP seals shells

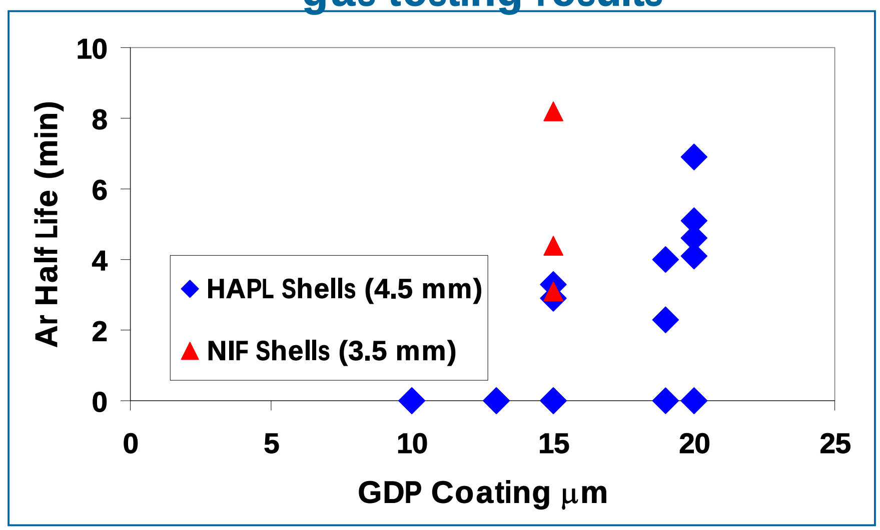
Potential pathways for overcoat:

- ***2-step process w/ polymerization coat plus a GDP coat***
- ***Direct coating with smaller-pore foam foam (~0.1 micron)***



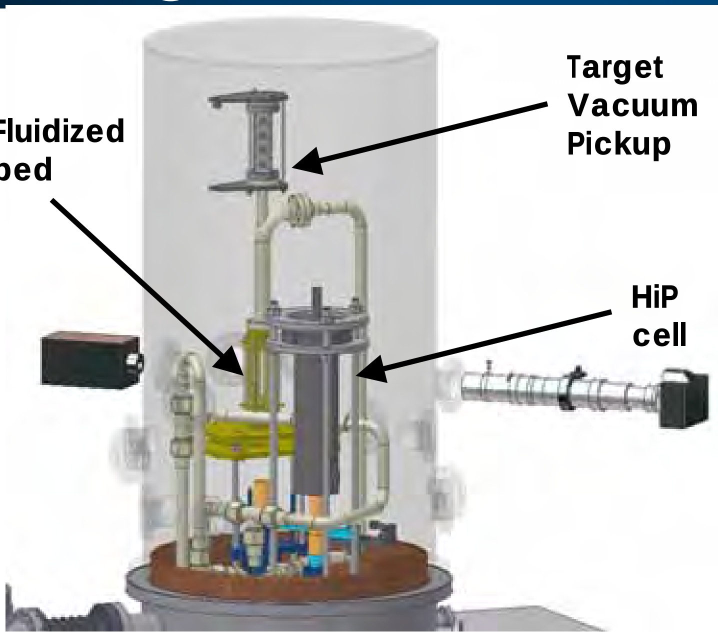
Current Spec

Initial GDP on resorcinol-formaldehyde (RF) small-pore foam gas testing results



GENERAL ATOMICS

3) Mass production layering experiment is being brought online …



- Key MPLX scoping tests done
- LANL studies on DT behavior
- Layering studies in ICF program still underway… (leverage)

Cryocoolers

Cryogenic circulator

UCSD

<u>~7 Students</u>

-UCSD (3)
-Chemistry (3)
-Fluidized bed (1 PhD)

Poster by Neil Alexander…

Includes filling with HD
(via permeation thru overcoats)

(4) Target injection has several acceleration options ...

Injection demo for >400 m/s

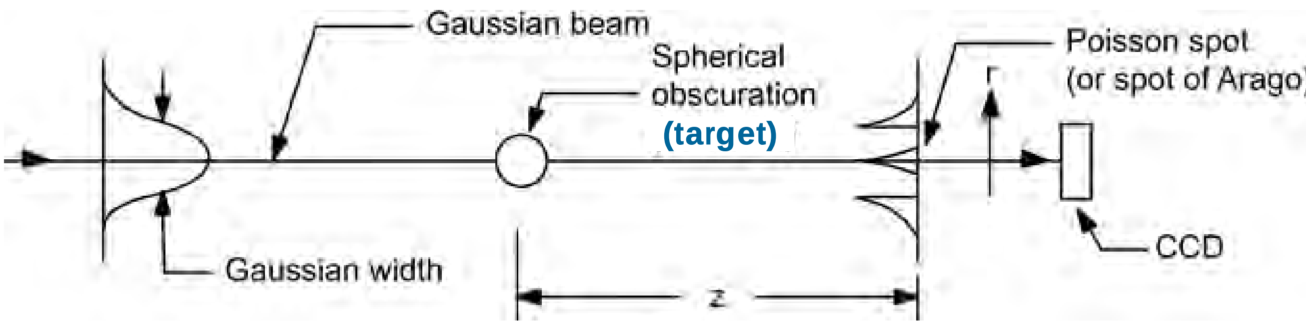
Magnetic diversion - reduces gas in chamber and heating and give more options

1. "Mechanical" (~50-100 m/s)
2. EM "Slingshot" (~60-85 m/s)

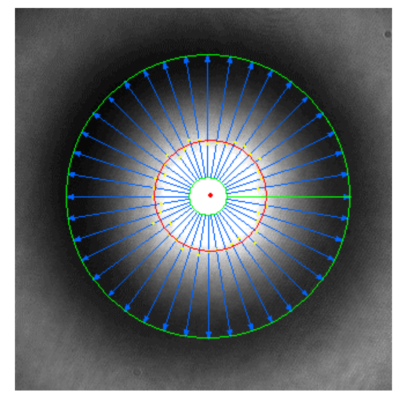
Poster by Ron Petzoldt ...

5) Tracking and alignment concepts identified and demonstrations underway

- **Laser fusion requirement is alignment of lasers and target to 20 μm**
- **Now demonstrating on optical table "in-chamber" systems ("continuous" tracking for mirror "pre-steering")**



UCSD



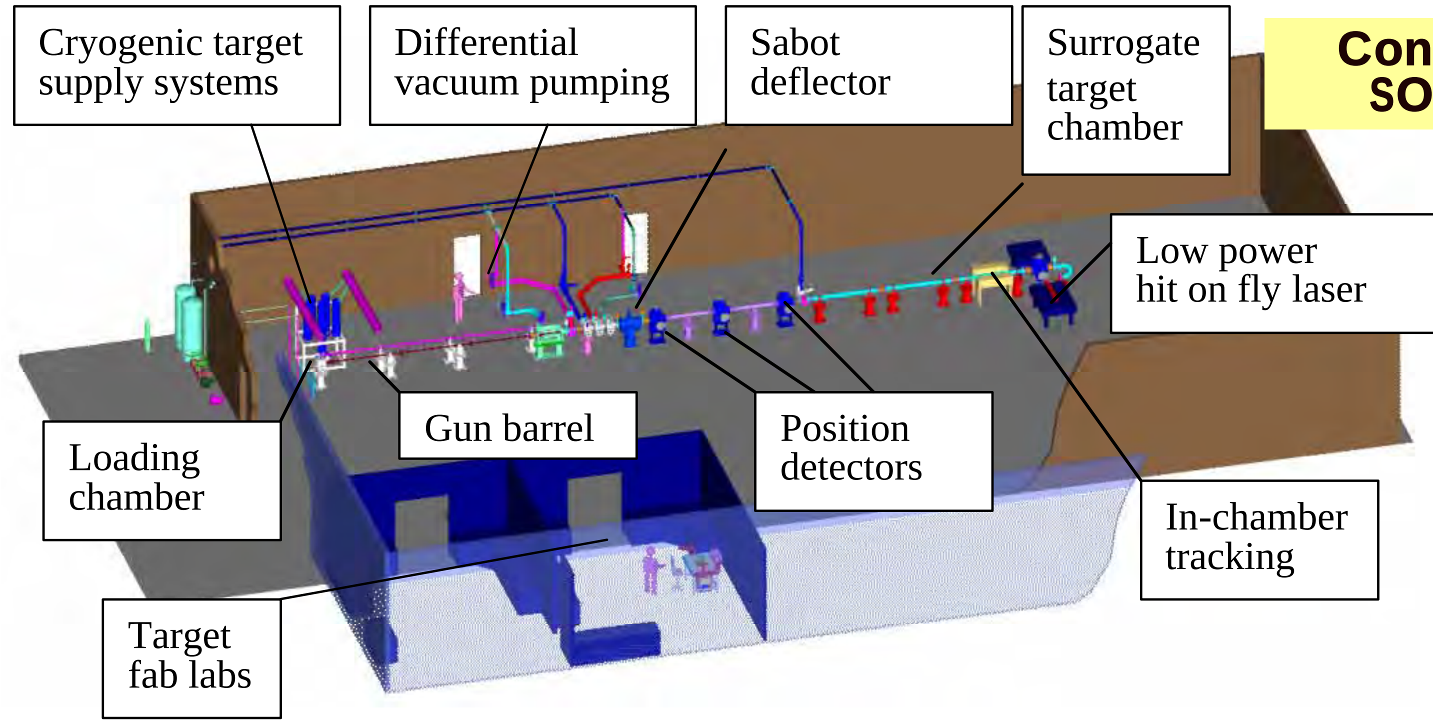
Poisson spot on CCD

- **Final steering by "glint" system that uses the target itself for final alignment of the mirrors and beamlines**

- **Optical table demo for "hit-on-the-fly" using "glint" is underway….**

Poster by Ron Petzoldt …

To the future - integration of cryogenics w/ injector



Concept from SOFE- 2003

M. S. Tillack et al, "A Target Fabrication and Injection Facility for Laser-IFE" SOFE-2003 14-17 October 2003, San Diego CA.

Mass layering device

Injector

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

Summary and conclusions

1. ***IFE target technology is leveraging the ICF program to extent possible***

2. ***Most recent progress has been on laser fusion***

3. ***Target supply scenarios have been identified for the IFE approaches***

4. ***Our emphasis for technology development is on near-term demonstrations of feasibility***